INNOVATIVE CONCEPTS FOR ON-LINE SYNCHRONOUS GENERATOR

PARAMETER ESTIMATION

by

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ABSTRACT

A method to identify synchronous generator parameters from on-line measurements is presented. Generator parameters are employed in the construction of models used in transient stability studies and other routine power engineering studies. These studies are critical for the operation of the power system, and therefore accurate representation of synchronous generators and their parameters is important. The existing off-line techniques are often not practical and do not capture the behavior of the generator at all operating levels. Generator parameters vary due to aging, changes of the generator internal temperature, magnetic saturation, and coupling between the generator and external systems. The method proposed in this dissertation estimates generator parameters at any operating level, taking into consideration the effect of saturation and other phenomena in the operation of the synchronous generator.

Estimation of synchronous generator parameters is a fairly complex mathematical procedure, and there is a need for an easily used mechanism for model parameter estimation. The proposed method is based on least squares estimation and on a simplified synchronous generator model. The method is developed to be used with a Visual C++ engine and graphic user interface (GUI), so that the practicing power engineer may link machine measurements taken in an on-line environment with the estimator. A GUI application which is user friendly and self guiding is presented.

An observer for the estimation of damper winding currents is developed. The observer constructs estimates of the damper winding currents by using voltage and current measurements from the system and *a priori* system knowledge. The observer is integrated into the parameter identification algorithm.

A saturation model of the inductances of the synchronous generator is proposed and implemented in the estimator. Saturation affects a number of inductances in the generator. Accurate representation of saturation leads to accurate estimates that reflect the true status of the machine at every operating point. Saturation in both the direct and quadrature axes of the generator is considered.

Results from both simulated and actual measurements are presented. The feasibility of each of the proposed models is evaluated. Parameter estimation is performed for a number of generators at different operating points to enhance the confidence in the proposed algorithm. It is possible to use the proposed method to track generator parameters over time so that impeding internal generator faults can be detected and remedial action can be undertaken to avoid costly outages.

ACKNOWLEDGMENTS

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NOMENCLATURE

a	a axis of a three phase system
A	$n \times n$ matrix of a linear system
abc	Stator per-phase quantities on conventional a-b-c axes
AC	Alternating current
A_d	Flux component of direct axis
A_{d0}	Flux component of direct axis where saturation starts
A_G	Saturation constant used in the calculation of the saturation function
ANN	Artificial neural networks
APS	Arizona Public Service Company
A_q	Flux component of quadrature axis
A_{q0}	Flux component of quadrature axis where saturation starts
ASCII	American Standard Code for Information Interchange
AT	Ampere-turns of a winding
b	b axis of a three phase system
B	$n \times m$ matrix of a linear system
B_G	Saturation constant used in the calculation of the saturation function
c	c axis of a three phase system
C	$p \times n$ matrix of a linear system
COMTRADE	IEEE Standard Common Format for Transient Data Exchange
D	Damper winding on the direct axis of a synchronous generator
D	$p \times m$ matrix of a linear system

DC   Direct current

DFR   Digital fault recorder

dq0   Stator transformation to direct, quadrature and zero axis parameters

E   Generator internal voltage, leading terminal voltage V

E $n \times p$ matrix used in a Luenberger observer to drive error to zero

EMF   Electromotive force

EMTP   Electromagnetic Transients Program

Estimator Application developed for on-line estimation of synchronous generator parameters

E_t Generator terminal voltage, also see V_t

FC4HP   High pressure unit of steam generator 4 located at Four Corners generating station

FC5HP   High pressure unit of steam generator 5 located at Four Corners generating station

FIR   Finite impulse response

$F(\vartheta)$ Air gap MMF distribution

G   Damper winding on the quadrature axis of a synchronous generator

GT1   Gas turbine unit 1, located at Redhawk generating station

GT2   Gas turbine unit 2, located at Redhawk generating station

GUI   Graphic user interface

H $m \times n$ matrix containing the coefficients of the unknown parameters

i   Instantaneous current

i_0 Stationary current, proportional to zero sequence current

i_{0dq} Vector containing the *odq* currents

i_a	Current through stator phase a
i_{abc}	Vector containing the abc currents
I_A	Field current at 1 p.u. voltage on air gap line
i_b	Current through stator phase b
I_B	Field current at 1 p.u voltage on open circuit characteristic
I_B	Stator current base
i_c	Current through stator phase c
I_C	Field current at 1.2 p.u voltage on open circuit characteristic
i_d	Current through direct axis
i_D	Current through damper winding D
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
i_F	Current through field winding
I_{FB}	Rotor current base
i_{FDGQ}	Vector containing rotor currents in both axes
I_{Frated}	Rated field current
i_G	Current through damper winding G
IIR	Infinite Impulse Response
I_{mxm}	Identity matrix of dimension m
i_n	Neutral current
i_q	Current through quadrature axis
i_Q	Current through damper winding Q

IRLS	Iteratively reweighted least squares
I_t	Current at the terminals of the generator
$J(x)$	Residual
k	Multiplying factor in Park's transformation, equal to $\sqrt{3/2}$
k	Constant representing the effect of saturation
K	Constant relating phase current and MMF in the winding
K	Degrees of freedom of the chi-squared distribution
K_{sd}	Saturation factor for direct axis
K_{sq}	Saturation factor for quadrature axis
L_0	Equivalent zero sequence inductance ($L_0 = x_0$ in p.u.)
L_1	1-norm or sum of absolute deviations norm
L_2	2-norm or least squares norm
L_∞	infinite norm or maximum norm
l_a	Stator phase winding a leakage inductance
L_{aa}	Stator phase winding a self inductance
L_{ab}	Stator phase winding a to b mutual inductance
L_{ac}	Stator phase winding a to c mutual inductance
L_{aD}	Stator phase winding a to damper winding D mutual inductance
L_{AD}	Direct axis magnetizing mutual inductance
L_{ADs}	Saturated direct axis magnetizing mutual inductance
L_{ADu}	Unsaturated direct axis magnetizing mutual inductance
L_{aF}	Stator phase winding a to field winding mutual inductance

L_{aG}	Stator phase winding a to damper winding G mutual inductance
L_{aQ}	Stator phase winding a to damper winding Q mutual inductance
L_{AQ}	Quadrature axis magnetizing mutual inductance
L_{AQs}	Saturated quadrature axis magnetizing mutual inductance
L_{AQu}	Unsaturated quadrature axis magnetizing mutual inductance
L_{aR}	3×4 matrix inductance matrix
L_B	Stator inductance base
L_{ba}	Stator phase winding b to a mutual inductance
L_{bb}	Stator phase winding b self inductance
L_{bc}	Stator phase winding b to c mutual inductance
L_{bD}	Stator phase winding b to damper winding D mutual inductance
L_{bF}	Stator phase winding b to field winding mutual inductance
L_{bG}	Stator phase winding b to damper winding G mutual inductance
L_{bQ}	Stator phase winding b to damper winding Q mutual inductance
L_{ca}	Stator phase winding c to a mutual inductance
L_{cb}	Stator phase winding c to b mutual inductance
L_{cc}	Stator phase winding c self inductance
L_{cD}	Stator phase winding c to damper winding D mutual inductance
L_{cF}	Stator phase winding c to field winding mutual inductance
L_{cG}	Stator phase winding c to damper winding G mutual inductance
L_{cQ}	Stator phase winding c to damper winding Q mutual inductance
l_d	Direct axis leakage inductance

l_D	Direct axis leakage inductance
L_d	Equivalent direct axis inductance
L_d'	Transient direct axis inductance ($L_d' = x_d'$ in p.u.)
L_d''	Subtransient direct axis inductance ($L_d'' = x_d''$ in p.u.)
L_{Da}	Damper winding D to stator phase winding a mutual inductance
L_{Db}	Damper winding D to stator phase winding b mutual inductance
L_{Dc}	Damper winding D to stator phase winding c mutual inductance
$L_{DD}=L_D$	Damper winding D self inductance
L_{DF}	Damper winding D to field winding mutual inductance
L_{DG}	Damper winding D to damper winding G mutual inductance
L_{DQ}	Damper winding D to damper winding Q mutual inductance
l_F	Field winding leakage inductance
l_{F1D}	Field winding to damper winding D mutual leakage inductance
L_{Fa}	Field winding to stator phase winding a mutual inductance
L_{Fb}	Field winding to stator phase winding b mutual inductance
L_{FB}	Field inductance base
L_{Fc}	Field winding to stator phase winding c mutual inductance
L_{FD}	Field winding to damper winding D mutual inductance
$L_{FF}=L_F$	Field winding self inductance
L_{FG}	Field winding to damper winding G mutual inductance
L_{FQ}	Field winding to damper winding Q mutual inductance
l_G	Damper winding G leakage inductance

L_{Ga}	Damper winding G to stator phase winding a mutual inductance
L_{Gb}	Damper winding G to stator phase winding b mutual inductance
L_{Gc}	Damper winding G to stator phase winding c mutual inductance
L_{GD}	Damper winding G to damper winding D mutual inductance
L_{GF}	Damper winding G to field winding mutual inductance
$L_{GG} = L_G$	Damper winding G self inductance
L_{GQ}	Damper winding G to damper winding Q mutual inductance
L_m	Stator phase winding magnetizing inductance
L_{md}	Direct axis magnetizing inductance
L_n	Equivalent neutral inductance
l_Q	Damper winding Q leakage inductance
L_q	Equivalent quadrature axis inductance ($L_q = x_q$ in p.u.)
L'_q	Transient quadrature axis inductance ($L'_q = x'_q$ in p.u.)
L''_q	Subtransient quadrature axis inductance ($L''_q = x''_q$ in p.u.)
L_{Qa}	Damper winding Q to stator phase winding a mutual inductance
L_{Qb}	Damper winding Q to stator phase winding b mutual inductance
L_{Qc}	Damper winding Q to stator phase winding c mutual inductance
L_{QD}	Damper winding Q to damper winding D mutual inductance
L_{QF}	Damper winding Q to field winding mutual inductance
L_{QG}	Damper winding Q to damper winding G mutual inductance
$L_{QQ} = L_Q$	Damper winding Q self inductance
L_{Ra}	4×3 inductance matrix

L_{RR}	3×3 inductance matrix
L_s	Stator phase winding inductance
m	number of measurements
MATLAB$^{®}$	MATrix LABoratory: Software package for high-performance numerical computations
M_D	Stator to damper winding D mutual inductance
M_F	Stator to field winding mutual inductance
M_{FB}	Field mutual inductance base
MFC	Microsoft foundation classes: used in Visual C++ programming
M_G	Stator to damper winding G mutual inductance
MIMO	Multiple input-multiple output
MMF	Magnetomotive force
MMF_a	MMF in phase a
MMF_{AD}	MMF in the direct axis
MMF_{AQ}	MMF in the quadrature axis
MMF_b	MMF in phase b
MMF_c	MMF in phase c
ML	Maximum likelihood
M_Q	Stator to damper winding Q mutual inductance
M_s	Stator phase winding mutual inductance
M_X	Direct axis mutual inductance
M_Y	Quadrature axis mutual inductance

n	Number of unknowns
N_a	Effective turns in phase a
NERC	North American Electric Reliability Council
N_m	Number of measurements
N_s	Number of states
OCC	Open circuit characteristic
ode	Ordinary differential equation
OEM	Output error estimation
p	Pulse order of harmonic component
P	Active power
P	Park's transformation matrix
P_0	DC component of permeance distribution
P_2	Amplitude of AC component of permeance distribution
PSERC	Power Systems Engineering Research Center
$P(\vartheta)$	Permeance distribution
Q	Reactive power
Q	Damper winding on the quadrature axis of a synchronous generator
QR	QR decomposition; a matrix is resolved into two matrices: Q and R
$r=r_a=r_b=r_c=R_1$	Stator resistance
R_B	Stator resistance base
r_D	Damper winding D equivalent resistance
r_F	Field winding equivalent resistance

R_{FB}	Field winding resistance base
r_G	Damper winding G equivalent resistance
RML	Recursive maximum likelihood
rms	Root mean square
r_n	Equivalent neutral resistance
r_Q	Damper winding Q equivalent resistance
S_B	Stator and rotor MVA base
SCC	Short Circuit Characteristic
SNR	Signal to noise ratio
SSFR	Standstill frequency response
ST1	Steam turbine unit 1, located at Redhawk generating station
ST2	Steam turbine unit 2, located at Redhawk generating station
SVD	Singular value decomposition
t	Time
t_B	Time base
TIF	Telephone Influence Factor
t_J	Threshold value of the residual $J(x)$
TVA	Tennessee Valley Authority
U_4	4×4 unit matrix
$u(t)$	$m \times 1$ vector of the input states to a system
v	Instantaneous voltage
V	Voltage phasor

v_0	Zero axis voltage, proportional to zero sequence voltage
V_0	Saturation threshold on OCC curve
v_{0dq}	Vector of *0dq* voltages
v_a	Stator phase *a* voltage
v_{ab}	Line to line voltage between phases *a* and *b*
v_{abc}	Vector of *abc* voltages
v_b	Stator phase *b* voltage
V_B	Stator voltage base
v_{bc}	Line to line voltage between phases *b* and *c*
v_c	Stator phase *c* voltage
v_{ca}	Line to line voltage between phases *c* and *a*
v_d	Direct axis voltage
v_D	Damper winding *D* voltage
V_{FB}	Field (rotor) voltage base
v_F	Field winding voltage
v_G	Damper winding *G* voltage
Visual C++	Microsoft Visual C++: Software package for development of graphical environments and user friendly interfaces
v_n	Neutral voltage component
v_q	Quadrature axis voltage
v_Q	Damper winding *Q* voltage
V_t	Generator terminal voltage
$w(t)$	$(n-p) \times 1$ state vector

x	Vector of unknown parameters in the matrix equation $Hx = z$
$\hat{x}$	Vector of estimated parameters in the matrix equation $Hx = z$
X	Reactance in Ω or in per unit
x_0	Equivalent zero sequence reactance
X_{AD}	Direct axis magnetizing mutual reactance
X_{ADu}	Direct axis unsaturated magnetizing mutual reactance
X_{AQ}	Quadrature axis magnetizing mutual reactance
X_{AQu}	Quadrature axis unsaturated magnetizing mutual reactance
x_d	Equivalent direct axis reactance
x'_{dv}	Transient direct axis reactance
x''_{dv}	Subtransient direct axis reactance
x_l	Stator leakage reactance
x_{Lm}	Stator leakage reactance
x_q	Equivalent quadrature axis reactance
x'_q	Transient quadrature axis reactance
x''_{qv}	Subtransient quadrature axis reactance
$x(t)$	$n \times 1$ vector of the states of a system
$y(t)$	$p \times 1$ vector of the output states of a system
z	Right hand side vector in the matrix equation $Hx = z$
$z(t)$	$(n - p) \times 1$ state vector of an observer to a system
α	Significance level for χ^2 test

α	Angle indicating the relative position of the direct and quadrature axes (0° and 90° respectively)
γ	Angle along the rotor periphery of the stator with respect to phase a
δ	Synchronous machine torque angle in electrical radians
ΔAT	Saturation component of flux
ΔAT_d	Saturation component of the flux in the direct axis
ΔAT_q	Saturation component of the flux in the quadrature axis
ΔH	Noise content in H matrix
$\Delta \hat{x}$	Estimated correction to the estimated parameters
Δt	Time step between measurements
Δz	Noise content in z vector
ϑ	Angular displacement of d axis from a axis in mechanical radians
λ	Instantaneous flux linkage
λ_0	Zero sequence flux linkage
λ_{0dq}	Flux linkage vector of $0dq$ components
λ_a	Flux linkage of axis a
λ_{abc}	Vector of stator flux linkages
λ_{ad}	Flux linkage in the direct axis
λ_{aq}	Flux linkage in the quadrature axis
λ_{at}	Terminal flux linkage
λ_b	Flux linkage of axis b
λ_c	Flux linkage of axis c
λ_d	Flux linkage of direct axis

λ_D	Damper winding D flux linkage
λ_F	Field winding flux linkage
λ_{FDGQ}	Vector of rotor flux linkages
λ_G	Damper winding G flux linkage
$\lambda_{I1.0}$	Value of the saturation function at 1 p.u. voltage
$\lambda_{I1.2}$	Value of the saturation function at 1.2 p.u. voltage
λ_I	Saturation function
λ_{Id}	Saturation function for direct axis
λ_{Iq}	Saturation function for quadrature axis
λ_q	Flux linkage of quadrature axis
λ_Q	Damper winding Q flux linkage
μ	Mean
σ	Standard deviation
τ'_{d0}	Direct axis transient open circuit time constant
τ''_{d0}	Direct axis subtransient open circuit time constant
τ'_{q0}	Quadrature axis transient open circuit time constant
τ''_{q0}	Quadrature axis subtransient open circuit time constant
$\Phi(\vartheta)$	Air gap flux distribution
$\Phi_d(\vartheta)$	Air gap flux distribution in the direct axis
$\Phi_q(\vartheta)$	Air gap flux distribution in the quadrature axis
χ^2	Variable for chi-square test

ω	Synchronous angular frequency in radians per second
ω_B	Base synchronous angular frequency in radians per second
Ω_c	Cutoff frequency of a low pass filter
ω_R	Rated synchronous angular frequency in radians per second
$\lvert \cdot \rvert$	Absolute value
$(\cdot)'$	Derivative of a variable or matrix with respect to time
$\wedge$	Estimated quantity
$(\cdot)^{-1}$	Inverse
$\lVert \cdot \rVert_p$	p norm of a vector, $p \geq 1$
$(\cdot)^+$	Pseudoinverse
$(\cdot)^T$	Transpose

CHAPTER 1

INTRODUCTION

1.1 Motivation

The main motivation of this work is the need for accurate models of synchronous generators. These models are used in transient stability studies and other routine power engineering studies. Standard parameters of synchronous generator models can be obtained from dedicated tests or from manufacturer data. The aim of this work is to estimate synchronous generator model parameters by utilizing recorded operating data. Estimation of synchronous machine model parameters is a fairly complex mathematical procedure, and there is a need for an easily used mechanism for model parameter estimation. A graphic user interface -menu driven- synchronous generator parameter estimator is developed to assist practicing engineers in the estimation process.

The research work described in this report was further motivated by the operating history of an 800 MW synchronous machine (unit #5) located at the Four Corners Generating Station of the Arizona Public Service Company (APS). This unit has undergone outages on a number of occasions due to a short circuit in its field winding. On each occasion that this outage occurred the rotor had to be rebuilt, thus leading to increased costs and possibly decreased reliability for the company. It is beneficiary to develop a method such that a short circuit in the field winding is detected promptly. In this way, remedial action or preventive measures can be taken so as to avoid costly outages. Since turn-to-turn shorts in the field winding in effect alter the field resistance, a measurement (or calculation) of this resistance in different time intervals may enable the user to monitor the unit for possible short circuits. Therefore, it is necessary to track over

time the estimate of the field resistance and to issue a warning when the resistance value falls below a specified limit. If, at any instance, the field resistance falls below the indicated limit, then the unit can be taken out of service and repaired to avoid a possible forced outage.

Generator parameters are in general not constant throughout the useful life of a synchronous generator. Some parameters, such as the magnetizing inductances in the direct and quadrature axes, vary at different operating points due to the effect of magnetic saturation. These and other parameters also change because of aging, since generator parameters are properties of physical materials in the generator windings that undergo changes in their physical characteristics as they age. Further, major changes in generator parameters occur after a repair. For example, rewinding of the rotor of a generator would cause the field resistance to be different than its designed value. For these reasons, parameter estimation is necessary to ensure that the parameters used in different power system studies are accurate, and to enhance the confidence in the interpretation of the results of such studies.

An additional motivation of this work is that regional coordinating councils (such as the North American Electric Reliability Council (NERC)) often require of their utility company members that generator parameter tests be done periodically. The development of on-line parameter estimators holds the promise of satisfying this requirement.

1.2 Objectives

The main objective of this research work is to develop a method to identify synchronous generator parameters from on-line measurements. It is also desired to develop a graphic user interface (GUI) application which will be user friendly and self guiding so as to facilitate prompt estimation of the desired parameters. In this way, possible fault conditions can be detected and remedy action can be undertaken. Moreover, it is necessary to develop an algorithm that will enable bad measurement detection and rejection so as to increase the reliability of the results. Another objective of this research work is to develop the saturation model of the inductances of a synchronous machine. A number of inductances in the synchronous machine model experience significant change in their values depending on the operating condition of the machine. The effect of saturation is modeled and incorporated it in the GUI so as to obtain accurate estimates that reflect the true status of the machine at every operating point.

Secondary objectives of the research include

- Development of an observer for damper currents

- Calculation of the error characteristics of the estimation

- Development of an index of confidence

- Calculation of a range of values for each estimated parameter

- Study of which machine parameters can be estimated, and which can not

- Evaluation of alternative GUI features.

Fig. 1.1 shows the activities related to a synchronous generator, their relation to the graphic user interface, and the estimation method proposed in this research work.

SYNCHRONOUS GENERATOR OPERATION		
Loading schedule	Synchronization and stabilization	Maintenance and parameter tracking

Reliability Coordination area requirements Generator history	Preventive maintenance	Forced outage analysis
Parameter tracking via GUI	Modeling and EMTP studies	Examination of tracked parameters through GUI

GRAPHIC USER INTERFACE

Damper current observer	Saturation model	*a priori* system knowledge
Park's transformation model	GUI features	Estimator

Fig. 1.1. Synchronous generator operation and graphic user interface implementation

1.3 Identification of synchronous generator parameters: an overview

The power system state estimation problem has attracted the attention of many researchers since the late sixties [1]-[3], [4]. The main aim was to develop a technique to monitor the power system and to calculate some of the system states by using other available data. The interest in generator parameter identification arose about a decade later.

Traditionally, synchronous generator parameters are obtained by manufacturer data sheets and then verified and enhanced by off-line tests, as described in IEEE Standards [5], [6]. Several researchers between 1969 and 1971 developed methods to find additional parameter values based on the synchronous generator models by Dandeno [7], Schulz [8], and Dineley [9]. Jackson and Winchester [10] developed direct and quadrature axis equivalent circuits for round rotor synchronous generators. During the same period, Canay [11] focused on developing equivalent circuits for field and damper windings to estimate generator parameters. A significant contribution was made by Yu and Moussa in 1971 [12] who reported a systematic procedure that can be implemented to determine the parameters of the equivalent circuits of synchronous generators.

Off-line methods, however, are neither practical nor accurate in most cases. Decommiting a generator for parameter measuring is not economical for a utility - especially if the specific generator is a base unit. Furthermore, under different loading conditions certain generator parameters may vary slightly and therefore off-line methods may not be accurate enough for certain applications. Finally, the effect of saturation of generator inductances cannot be accounted for in off-line studies. Saturation is a critical

concept in generator operation; in order to consider it in the estimation process, one has to account for the operating level of the generator at the particular estimation interval [5], [13]-[15].

Contrary to off-line methods, on-line methods to identify machine parameters are very attractive to utilities because of their minimal interference in the normal operation of the generator. Ideally, generator parameters may be calculated under different operating conditions, both in steady state and transient operation. In 1977 Lee and Tan [16] proposed an algorithm to determine the parameters of a salient pole generator from data obtained during a sudden short circuit. In 1981, Dandeno [17] used on-line frequency response measurements from two large turbo generators to identify machine parameters; during the same period, Nishiwaki [18] used the extended Kalman filter to identify dynamic stability constants for small disturbances under steady state operating conditions. In 1982 Bollinger [19] proposed a technique to estimate system parameters by utilizing wide bandwidth noise signals in an excitation signal which acts as a disturbance to the system.

1.4 Literature review

The literature search for this research work focuses mainly on the following topics:

- Analysis and modeling of synchronous generators

- Estimation of parameters of synchronous generators

- Differential equations and their numerical solutions

- Estimation techniques and the generalized inverse

- Computer analysis methods

- Noise filtering

- Observers and observability

- Magnetic saturation.

- Analysis and modeling of synchronous generators

The classic Westinghouse Transmission and Distribution Handbook provides information for the construction and operation of synchronous machines [20]. Another useful handbook in the field of electrical machinery is the *Electric Motor Repair* by Rosenberg [21]. It is a handbook for the "practically minded" concentrating on the winding, repair, and troubleshooting of a large number of AC and DC motors and controllers. *Power System Stability and Control* by Kundur [13] and *Power System Control and Stability* by Anderson and Fouad [14] provide an extensive and detailed analysis of synchronous machines, in both theory and modeling. They dedicate three chapters on this topic and, among others, they cover the *dq0* transformation, the per unit representation, equivalent circuits, and analysis in both steady state and transient operation. Saadat in *Power System Analysis* [22] concentrates on the transient analysis of the synchronous generator and on balanced and unbalanced faults. Saadat offers coverage on the Park's transformation and on deriving the generator equation in the rotor frame of reference.

Anderson, Agrawal, and Van Ness [23] provide an extensive analysis of synchronous machines. They dedicate a chapter on synchronous machine modeling and provide an extensive analysis of the direct and quadrature axis equations. They also examine thoroughly Park's transformation, while in one of their chapters they concentrate on parameter computation, measured data from field tests, and sample test results. Very useful sources of information are the books *Electric Machinery* [24] and *Analysis of Electric Machinery* [25]. Both books contain the theory of synchronous machines and analysis of steady state operation. In addition, [25] offers interesting details on operational impedances and time constants, linearized equations, and a chapter on the asynchronous and unbalanced operation of synchronous machines.

- Estimation of parameters of synchronous generators

As mentioned in Section 1.3, the interest in the field of synchronous generator parameter estimation arose in the late sixties. In the last fifteen years, this interest was enhanced by a number of researchers.

Keyhani, who has conducted research on parameter estimation using a number of different techniques, has offered extensive literature on this topic. One of the methods used by Keyhani was the estimation of parameters from Standstill Frequency Response (SSFR) test data [26], [27]. In this approach, curve fitting techniques are used to derive the transfer functions of the direct axis and quadrature axis using the available test data. The parameters of the model are then calculated from nonlinear equations, which relate the machine parameters and the time constants corresponding to the transfer functions

[27]. However, noise-corrupted data cause multiple parameter sets to be estimated. To obtain a unique set of parameters, Keyhani used a maximum likelihood estimation (ML) technique [26]. The results indicate that a unique and relatively accurate parameter set is estimated even though the data are corrupted with noise.

Keyhani in [28] offers an evaluation of the performance of the ML method using case studies and SSFR data from tests on a 722 MVA generator. It is shown that the ML method gives estimates with very small error, while the noise has no noticeable effect on the estimator. The ML algorithm and SSFR data were also used in [29] to estimate parameters of a three phase salient pole 5 kVA synchronous machine. The equivalent circuit models were developed and on-line dynamic responses were performed to validate the identified models.

Tsai, Keyhani, Demcko, and Farmer used small-disturbance responses and the ML estimation technique to identify an on-line synchronous generator model [30]. The first step was to identify the machine linear model parameters. Consequently, the saturation models of the machine were identified using the estimated mutual inductances under a wide range of operating conditions. It was shown that when the MMF saturation model was used, the simulated responses of the developed model matched closely with the measured responses.

Another method used by Keyhani was the identification of synchronous machine linear parameters from standstill step voltage input data [31]. The procedure involves applying a step voltage as an input and estimation of the parameters of the time constant and equivalent circuit models. The initial values of the parameters to be estimated are

extracted from the operational inductances which are derived from the measured time domain data.

Tsai, Keyhani, Demcko, and Selin presented a new approach to develop a model of the saturated synchronous generator using artificial neural networks (ANN) [32]. ANN are possible to be trained after being arranged in a certain pattern. The pattern used in this network is a feed-forward network and the learning scheme is of the error back-propagation form. Moreover, the training pattern was based on on-line small disturbance responses and the ML algorithm. The important conclusion of this paper is the fact that the developed ANN saturation model is capable of predicting the machine nonlinear changes which were not used in the training process.

Eitelberg in [33] uses a linearly formulated least squares problem to obtain approximate parameter values. Consequently, a numerical search method is used to solve the nonlinear problem of magnitude and phase fitting. Boje [34] proposes time domain measurements for determining selected parameters of synchronous machines. These are proposed as an alternative to standstill frequency domain tests, since as the authors argue, the proposed method uses simpler equipment and model parameters are obtained directly in parametric form. However, as with traditional SSFR testing, this method does not model the machine at normal operating conditions.

Karayaka, Keyhani, Agrawal, Selin, and Heydt in [35]-[37] concentrated on large synchronous utility generators to develop a procedure of parameter estimation from on-line measurements. In [35] a one-machine infinite bus system is simulated in the *abc* frame of reference using parameters provided by the manufacturer. The armature circuit

parameters are hence calculated using the recursive maximum likelihood (RML) estimation technique. Based on these estimates, the field winding and some damper parameters are estimated using an Output Error Estimation (OEM) technique. It is found that even with highly corrupted data the estimated and actual parameters are in good agreement. In [36] the authors present a method to estimate machine parameters using synthetic data as previously, but also real time operating data from a utility generator. This study showed that noise-corrupted data could be handled up to a certain point. Below a certain signal-to-noise ratio (SNR), estimation of machine parameters was not possible. The estimation of machine parameters using data obtained on-line showed that there was a reasonable agreement between estimated and actual curves.

The above methods were repeated by the authors using Artificial Neural Networks [37]. The data used to train the ANN were taken from real time operating data and the developed models were validated with measurements not used in the training of ANN and with large disturbance responses. It was shown that ANN models could correctly interpolate between patterns not used in training.

Rico, Heydt, Keyhani, Agrawal, and Selin attempted to estimate machine parameters using orthogonal series expansions such as Fourier, Walsh, and Hartley series [38], [39]. In [38] the authors propose the use of the Hartley series for fitting operating data such as voltage and current measurements and the use of linear state estimation to identify the coefficients of the series. In this way, the machine parameters can be identified. At the same time, this method is tested for noise corruption in the measurements. The authors show that the error in the estimation is below 1% even for

SNR of 50:1. In [39] the authors expand their previous study to include Walsh and Fourier series in machine parameter estimation. A matrix of coefficients common to all orthogonal series expansions is used. The results show that the estimated parameters are in good agreement with the actual parameters. Also, this method takes into account the dependence of the parameters with respect to the operating point. More information on orthogonal series expansions for various power system components such as synchronous generators and transmission lines can be found in [40].

Finally, Kyriakides and Heydt in [41] and [42] offer an algorithm for the estimation of synchronous generator parameters from measurements that are taken at the machine terminals while the generator serves its load. This report is an extension of the idea presented in the papers.

- Differential equations and their numerical solutions

The need to numerically solve differential equations is of particular importance in this research work. The model under study involves coupled differential equations, which have to be solved iteratively for data generation and program testing. The Taylor series uses a pth order series to estimate the solution. The Euler series uses the first two terms of the Taylor series, resulting in a first order approximation that has an error of the order of the time step used. If the time step is small enough (the size depends on the application), then the Euler method is a good approximation that can be easily implemented. Multistep methods are also available such as the midpoint method, the Milne's method and the Adams-Bashforth method. These, however, require more than

one starting value and are hence difficult to implement. Coverage and examples of the above methods are offered in [43], [44]. Other methods such as the trapezoidal and the parabolic methods can also be found in the literature [43], [45]-[48].

Perhaps the most widely used method, because of its ease of programming and accuracy, is the Runge-Kutta-Fehlberg integration method. Many variations of this method are available in computer packages such as MATLAB. Perhaps the most famous methods are those incorporated in the ode23 and ode45 m-files provided by MATLAB [49]. ode23 uses a simple second and third order pair of formulas for medium accuracy while ode45 uses a fourth and fifth order pair for higher accuracy. Detailed explanation of these methods can be found in [43], [45], [48].

- Estimation techniques and the generalized inverse

Estimation techniques such as state estimation, least squares, and maximum likelihood are used in engineering applications interchangeably. For the purposes of this research the mathematical model is desired to be transformed in a form realizable by a state estimation algorithm. State estimation is a process during which a number of unknown system state variables or parameters are assigned a value based on measurements from that system [50].

Schweppe [1]-[3] was one of the first to propose and develop the idea of state estimation for the monitoring of power systems. Wood and Wollenberg dedicate a chapter of their book on state estimation [50]. They offer insight to maximum likelihood concepts and derive the least squares equations used in state estimation. An introduction

on advanced topics on state estimation and a lot of examples on AC network state estimation are offered. Advanced topics include bad data detection, estimation of quantities not being measured, network observability, and pseudo-measurements.

A book for the fundamentals of state estimation is that by Heydt [43]. It offers an introduction to state estimation and its applications in power engineering. Moreover, it proceeds in more advanced sections such as bad data identification and accuracy of state estimators. Information on the generalized inverse or pseudoinverse that will be used in this research can be found in both Heydt [43] and Wollenberg [50]. Albert [51] offers the theory behind the pseudoinverse and different manipulations or transformations of the inverse itself.

- Computer analysis methods

A major part of this research is the use of computer packages such as MATLAB and Visual C++ for the filtering of the measured signals, the implementation of the state estimation algorithm, and the development of a graphic user interface. Computer analysis methods are therefore of fundamental importance. A book in this area is the book by Heydt [43], which provides theory and practical applications on a number of topics applicable to this research work. Moreover, state estimation and the pseudoinverse are extensively covered as mentioned in the previous section.

Pratap [52] offers a helpful guide for MATLAB. Visual C++ and MFC programming are treated in several books [53]-[57]. No book suffices in itself because of

the vast capabilities of this programming language and the specialized functions of this application.

- Noise filtering

In between the data acquisition and the estimator implementation there are a number of other processes that need to be performed to prepare the data in a form that can be used by the estimator. One of the most fundamental processes is the filtering of the measured data for the removal of inconsistent measurements and noise. Various filters have been developed and implemented for the purposes of noise filtering. The filters considered for this work are digital discrete filters. Representative types of digital filters are the Butterworth, Chebyshev, Bessel, and moving average filters [58]-[60].

A filter almost always introduces a phase shift to the filtered signal. This phase shift is not desired, since the various frequency components of the signal are phase shifted by a different amount. Therefore, a zero phase shift filter is desired to be implemented so that there is no phase difference between the original and filtered signals. Information on zero phase shift filters can be found in [59], [61]-[63]. Zero phase digital filters effectively filter the signal in both the forward and the reverse directions. The resulting sequence has zero phase distortion and twice the filter order.

Bad data detection and rejection algorithms have been considered and implemented to remove outliers from the measurements. Such outliers appear in the form of spikes in the data sets and are inconsistent measurements. References [64]-[66]

propose new methods for the implementation of bad data detection and rejection algorithms in power system state estimation problems.

- Observers and observability

The theory of observers and observability is a well researched area in control systems with vast applications in other areas as well. Observers are utilized in this research work to identify unmeasurable signals in order to facilitate the estimation process. Various sources can be used to familiarize with the concept of an observer. DeRusso [67] and Luenberger [68] address the subject of observers and observer design. The two papers by Luenberger [69], [70] are state of the art in the field of control systems and they are the first to introduce what has later been known as the Luenberger observer. Luenberger observers are considered in Chapter 4.

- Magnetic saturation

Saturation of the generator magnetic circuits is an important concept in this research work. The effect of saturation has been the subject of many scientific papers and is still a subject of active research due to the importance of the change of the generator parameters with operating conditions and the difficulty for modeling saturation accurately. Reference [71] identifies saturation representation as the most important factor in the improvement of synchronous machine models. Saturation and different methods to model it are considered in IEEE standards such as [5], as well as a number of research articles and books [11], [13]-[15], [72], [73]. Fig. 1.2 shows a sample saturation

curve for a synchronous generator. Chapter 3 discusses magnetic saturation and its modeling in detail.
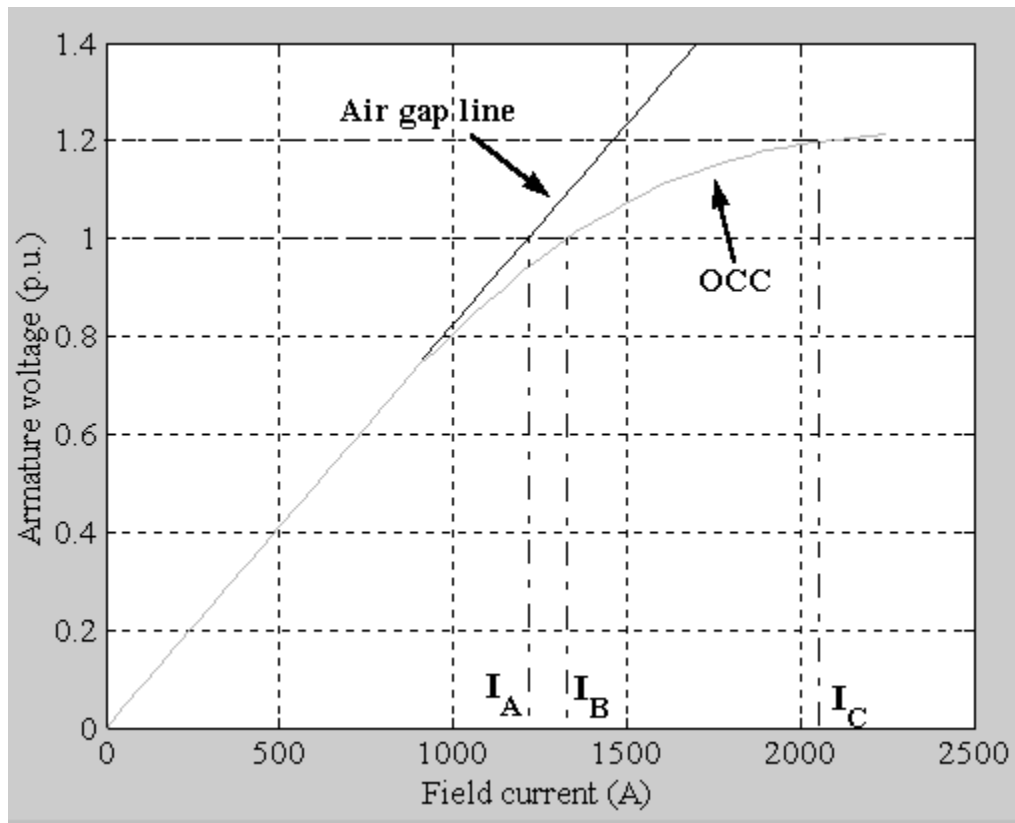
Fig. 1.2. Sample saturation curve for a synchronous generator

In [15], [72] the authors propose two quadratic saturation functions to represent saturation and they fit the proposed functions with measured data from two generators. This is performed using the method of finite element analysis. Reference [74] compares two methods of saturation representation by examining results of calculations and available test data for a specific synchronous generator. Saturation in both the direct and quadrature axes is considered. Authors in [75] describe a maximum likelihood

estimation algorithm to identify saturated inductances of a synchronous machine. The saturation was modeled from operating data that were generated from small voltage excitation disturbances. An alternative method to model saturation by using a linearized generator model and stochastic approximation to solve for the parameters of the model is presented in [73]. The authors in [76] present a saturation representation by using a finite element numerical analysis technique. However, the method does not apply to all operating conditions.

1.5 Statement of originality

The research work described in this dissertation is a contribution to electric power engineering and especially to the field of synchronous generators. A number of the research findings deserve mention in this section. References [41], [42], and [77]-[81] document the author's main publications related to this research.

A method to estimate synchronous generator parameters will be shown in this report. The results from the parameter estimation show considerable improvement over studies performed in the last few decades. The method was applied to a number of synchronous generators from different manufacturers and different generating stations. The parameters were estimated at various operating levels and the results, as presented in this dissertation, show a consistency among data sets of same machines.

An observer has been developed for the identification of damper winding currents. Damper windings appear in the synchronous generator model and the knowledge of these currents is instrumental in the estimation process. It should be noted

that this is the first time that a method for the estimation of damper winding currents is developed. The method was verified through simulation data, since it is currently not possible to obtain actual measurements of damper winding currents. The method was subsequently applied to the estimation of damper currents from actual generator data.

Finally, a method to estimate the quadrature axis characteristic from the available direct axis characteristic is described. A saturation model has been developed for use in on-line identification of synchronous generator parameters. The saturation model accounts for the operating point of the machine and corrects the mutual inductances that are affected by saturation.

CHAPTER 2

MODELING OF SYNCHRONOUS GENERATORS

2.1 System identification

The system identification procedure consists of a number of processes depending on the type of the task that is desired to be performed. In general, there are three basic entities that need to be available in order to perform any kind of system identification. These entities are the availability of a data set for the system, a set of candidate models, and an identification method or rule that will be used to identify the system parameters [82]. The system identification procedure is an iterative process with respect to the selection of the model of the system. A number of candidate models need to be tested so as to select the one that fits best to the actual response of the system. The selection process can be aided by the use of *a priori* knowledge of the system behavior and expected parameters, and by the comparison of the error characteristics obtained by each model. Fig. 2.1 shows the procedure that is followed in the system identification problem described in this report. This chapter concentrates on the selection of a model for the synchronous generator to be used in the identification procedure.

2.2 Model selection

In order to formulate the state estimation equation for a synchronous generator, it is necessary to employ a mathematical model, which will represent the synchronous generator in the conditions under study. There are a number of practical models available for synchronous generators depending on the type of study that is desired to be performed and the level of detail that the generator windings are modeled. Regardless of the model

chosen, it is necessary to consider an arrangement of three stator windings that are 120 electrical degrees apart, and a rotor structure that has at least one field winding and a variable number of damper windings in the direct and quadrature axes. The configuration of the rotor structure is the one that differentiates the various models of synchronous generators.
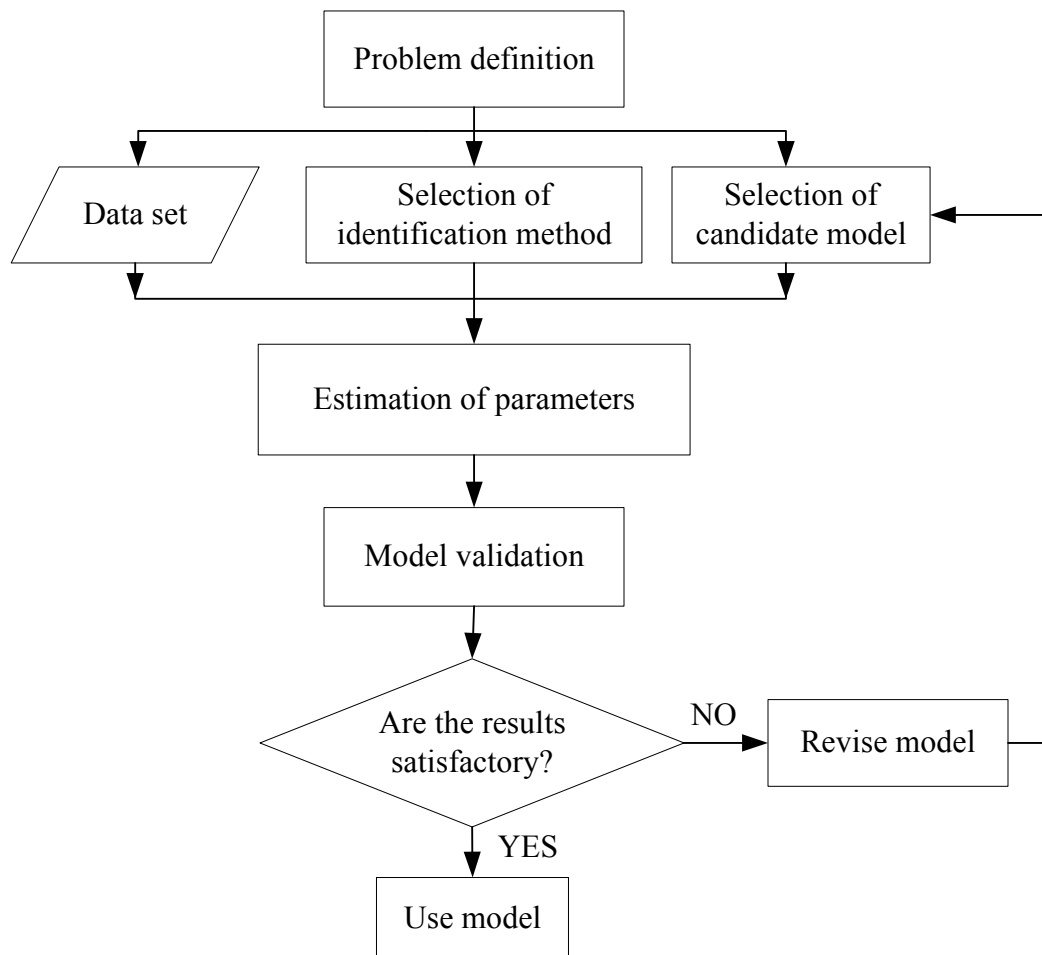
Fig. 2.1. System identification procedure

The order of a synchronous generator model is dictated by the number of rotor circuits in the direct and quadrature axes and usually ranges from first order to third order. Practical experience backed by simulation results and results from field tests show that a third order representation suffices for detailed analysis of synchronous generators. Lower order models are often used in a variety of studies (for example, stability studies) or for the representation of various types of generators (for example, hydro generators and turbine generators).

Various recommended synchronous generator models are suggested in IEEE standards, such as in [83]. Models 2.1 and 2.2, as shown in Figs 2.2 and 2.3 respectively, have been selected as candidates to perform the system identification procedure. The criterion for the selection of the two models was twofold: enough detail to obtain accurate estimates and simplicity in the model structure to make the estimation process simple to develop and program. Model 2.1 comprises one field winding and one damper (amortisseur) winding in the direct axis, and one damper winding in the quadrature axis. Model 2.2 has the same number of circuits in the direct axis, but has two damper windings in the quadrature axis to develop a symmetric model. In this chapter model 2.2 will be analyzed since the development of the model equations is similar for both models.
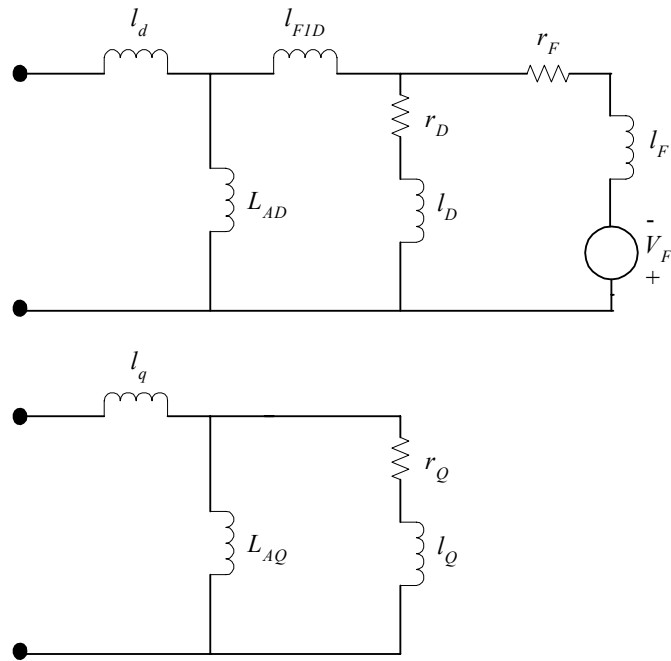
Fig. 2.2. Generator model 2.1 with one damper winding in each axis [83]
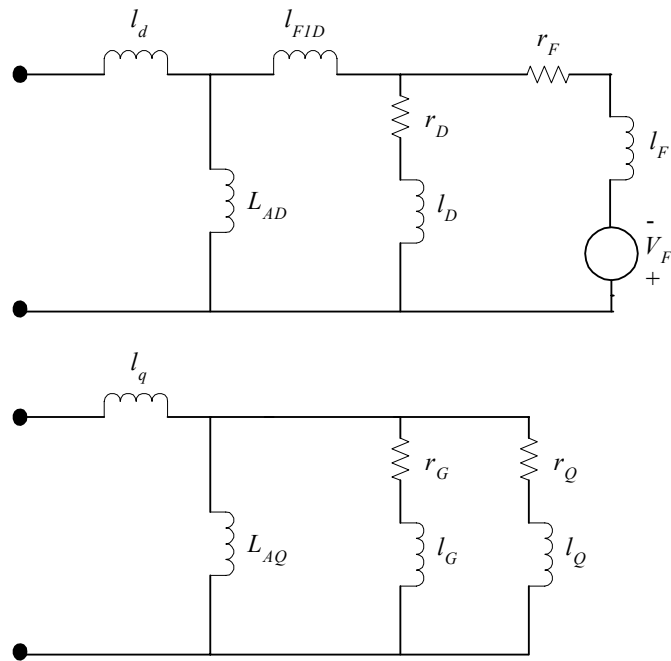
Fig. 2.3. Generator model 2.2 with one *d* axis and two *q* axis damper windings [83]

2.3 Modeling of synchronous generators

The synchronous generator model that will be analyzed in the remainder of this chapter is model 2.2, as defined in [83]. This model comprises three stator windings that are 120 electrical degrees apart and one rotor structure that is composed of two imaginary axes: the direct axis and the quadrature axis. The direct axis (*d* axis) comprises one field winding and one damper winding, while the quadrature axis (*q* axis) comprises two damper windings. The two damper windings on the *q* axis assist in obtaining a symmetric model with respect to the two imaginary axes and are particularly useful in the correct representation of round rotor synchronous generators. Measurements of the currents and voltages in the three stator windings and the field winding are usually available, and these will therefore be used as the states of the model under consideration. The damper currents in a synchronous generator are not possible to be measured. This shortcoming will be dealt with in Chapter 4 where an *observer* for the estimation of the damper currents will be presented.

The seven windings mentioned above (three in the stator and four in the rotor) are magnetically coupled. This coupling is a function of the rotor position and therefore the flux linking each winding is also a function of the rotor position [14]. Hence, the instantaneous terminal voltage of any winding takes the form,

$$v = -ri - \lambda',$$

(2.1)

where *r* is the winding resistance, *i* is the current, and λ is the flux linkage. The prime symbol (′) denotes a derivative with respect to time. It should be noted that in this notation it is assumed that the direction of positive stator currents is out of the terminals,

since the synchronous machine under consideration is a generator [25]. Before proceeding further with this derivation, it will be useful to refer to the Park's transformation which will be an essential tool for this analysis.

2.4 Park's transformation

In the late 1920s Park [84], [85] formulated a change of variables which replaced the variables associated with the stator windings of synchronous machines with variables associated with fictitious windings that are rotating with the rotor [25]. The configuration of these fictitious windings is illustrated in Fig. 2.4. The direction of rotation and the alignment of the d axis and q axis are defined in agreement with IEC Standard 34-10 [86] and IEEE Standard 100-1984 [87].

Park's transformation eliminates the time-varying inductances from the voltage equations. Stanley [88], Kron [89], and Brereton [90] also worked on this subject and developed similar equations transforming either the rotor or the stator variables to variables in fictitious windings in different reference frames. In the case of the synchronous machine, the time-varying inductances can be eliminated only if the reference frame is fixed in the rotor and therefore Park's transformation will be used [25]. It should be noted that the transformation that will be used in this chapter is not exactly the same as the one suggested by Park [84], [85], but rather an improvement of Park's method as suggested by various researchers such as Lewis [91], Concordia (discussion in [91]), and Krause and Thomas [92]. Since Park was the first to propose the method of

changing the variables associated with the stator windings, the transformation is named

after Park.
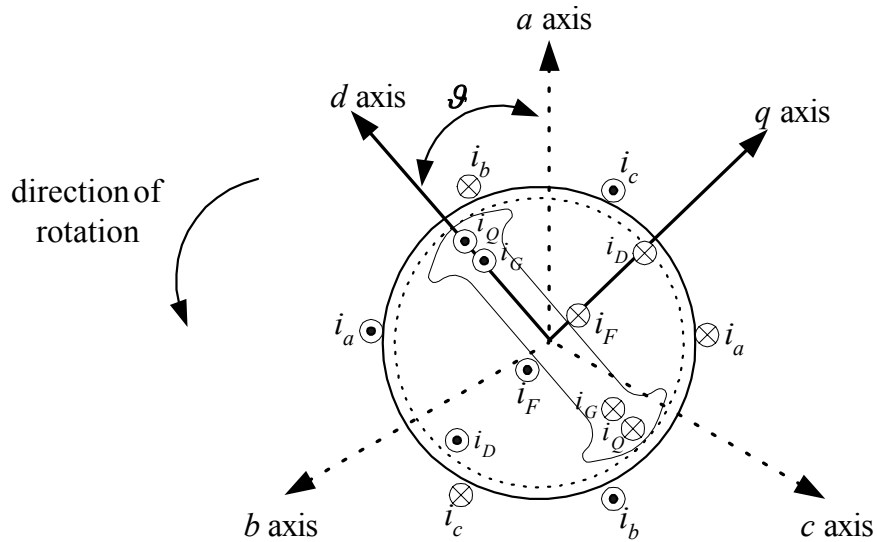
Fig. 2.4. Representation of a synchronous generator

The *d* axis of the rotor is defined to be at an angle ϑ radians with respect to a

fixed reference position at some instant of time. If the stator phase currents i_a, i_b, and i_c

are projected along the *d* and *q* axes of the rotor, the following relationships are obtained,

$$i_q = (2/3) \times [i_a \sin\vartheta + i_b \sin(\vartheta - 2\pi/3) + i_c \sin(\vartheta + 2\pi/3)]$$
$$i_d = (2/3) \times [i_a \cos\vartheta + i_b \cos(\vartheta - 2\pi/3) + i_c \cos(\vartheta + 2\pi/3)] . \tag{2.2}$$

It should be noted that in this formulation, the reference axis was chosen to be axis *a*, to

avoid an extra angle of displacement in all the terms.

The effect of the above transformation is to convert the stator quantities from

phases *a*, *b*, and *c* to new variables, the frame of which moves with the rotor. However,

since there are three variables in the stator, it is necessary to have three variables in the

rotor for balance. The third variable is on a third axis: the stationary axis. It is a

stationary current proportional to the zero-sequence current and it is zero under balanced conditions. Therefore, from (2.2), a matrix P called Park's transformation is defined, such that,

$$i_{0dq} = Pi_{abc},$$

(2.3)

where the current vectors are defined as,

$$i_{0dq} = \begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} \text{ and } i_{abc} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}.$$

(2.4)

The Park's transformation is thus defined as,

$$P = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos\vartheta & \cos(\vartheta - \frac{2\pi}{3}) & \cos(\vartheta + \frac{2\pi}{3}) \\ \sin\vartheta & \sin(\vartheta - \frac{2\pi}{3}) & \sin(\vartheta + \frac{2\pi}{3}) \end{bmatrix}.$$

(2.5)

It is apparent, that in order to perform this transformation it is necessary to calculate the angle ϑ. The flux of the main field winding is along the direction of the d axis of the rotor. This flux produces an EMF that is lagging by 90°. Therefore, the machine EMF E is mainly along the q axis of the rotor [14]. If a machine with terminal voltage V is considered, the phasor E should lead the phasor V if this machine is to be operated as a generator. The angle between E and V is denoted as the machine torque angle δ if V is in the direction of phase a (reference phase). Considering Fig. 2.2, at time $t = 0$, the phasor V is located at the reference axis a. The q axis is located at an angle δ and the d axis is located at an angle $\vartheta = \delta + \pi/2$. At $t > 0$, the reference axis is located at an angle $\omega_R t$ with respect to axis a. Therefore, the d axis of the rotor is located at,

$$\vartheta = \omega_R t + \delta + \pi/2 \quad \text{rad}, \tag{2.6}$$

where ω_R is the rated (synchronous) angular frequency in rad/s and δ is the synchronous torque angle in electrical radians.

Park's transformation can also be used to convert voltages and flux linkages from *abc* quantities to *0dq* quantities. The expressions are identical to the expressions for the current and are given by,

$$v_{0dq} = Pv_{abc} \text{ and } \lambda_{0dq} = P\lambda_{abc}. \tag{2.7}$$

Furthermore, if the transformation is unique, an inverse transformation exists, and the *abc* quantities can be calculated if the *0dq* quantities are known. In this case,

$$i_{abc} = P^{-1} i_{0dq}, \tag{2.8}$$

where the inverse Park's transformation is given by,

$$P^{-1} = \sqrt{\tfrac{2}{3}} \begin{bmatrix} \tfrac{1}{\sqrt{2}} & \cos\vartheta & \sin\vartheta \\ \tfrac{1}{\sqrt{2}} & \cos(\vartheta - \tfrac{2\pi}{3}) & \sin(\vartheta - \tfrac{2\pi}{3}) \\ \tfrac{1}{\sqrt{2}} & \cos(\vartheta + \tfrac{2\pi}{3}) & \sin(\vartheta + \tfrac{2\pi}{3}) \end{bmatrix}. \tag{2.9}$$

Park's transformation is an orthogonal matrix. This can be shown by examining the column vectors of the matrix. The column vectors of P are orthonormal since $u \cdot v = 0$ and $\|u\| = 1$ for every u, v in P. Then by definition the matrix P is orthogonal and $P^T P = I$. Since the inverse of a square matrix is unique, it is also true that $PP^T = I$. This implies that $P^{-1} = P^T$. Consequently, P is power invariant and therefore the same power expression can be used in both the *abc* and *0dq* frames of reference [14]. It is easy to show that,

$$p = v_a i_a + v_b i_b + v_c i_c = v_0 i_0 + v_d i_d + v_q i_q . \tag{2.10}$$

2.5 Formulation of voltage equations

As mentioned in Section 2.3 the mathematical model to be developed is of the form depicted in (2.1). As shown in Fig. 2.4 there are seven mutually coupled coils: the three phase windings, the field winding and one damper winding on the direct axis, and two damper windings on the quadrature axis. Therefore, the flux linkage equations for these windings result in,

$$\begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \\ \lambda_F \\ \lambda_D \\ \lambda_G \\ \lambda_Q \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} & L_{aF} & L_{aD} & L_{aG} & L_{aQ} \\ L_{ba} & L_{bb} & L_{bc} & L_{bF} & L_{bD} & L_{bG} & L_{bQ} \\ L_{ca} & L_{cb} & L_{cc} & L_{cF} & L_{cD} & L_{cG} & L_{cQ} \\ L_{Fa} & L_{Fb} & L_{Fc} & L_{FF} & L_{FD} & L_{FG} & L_{FQ} \\ L_{Da} & L_{Db} & L_{Dc} & L_{DF} & L_{DD} & L_{DG} & L_{DQ} \\ L_{Ga} & L_{Gb} & L_{Gc} & L_{GF} & L_{GD} & L_{GG} & L_{GQ} \\ L_{Qa} & L_{Qb} & L_{Qc} & L_{QF} & L_{QD} & L_{QG} & L_{QQ} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_F \\ i_D \\ i_G \\ i_Q \end{bmatrix}, \tag{2.11}$$

where L_{jk} is a self-inductance when $j = k$ and a mutual inductance when $j \neq k$. The stator inductances and the coupled inductances between the stator and the rotor are time varying inductances, while the rotor inductances are constants. Expressions for the inductances in (2.11) are given below.

- Stator self-inductances

$$\begin{aligned}
L_{aa} &= L_s + L_m \cos 2\vartheta \\
L_{bb} &= L_s + L_m \cos 2(\vartheta - 2\pi/3) \\
L_{cc} &= L_s + L_m \cos 2(\vartheta + 2\pi/3)
\end{aligned} \tag{2.12}$$

L_s and L_m are constants and $L_s > L_m$. The double frequency term (2ϑ) occurs due to the rotor saliency and the fact that the self-inductances are the same for both poles of the rotor [23].

- Stator mutual inductances

    The stator to stator mutual inductances are a function of rotor position since they are influenced by rotor saliency.

$$
\begin{aligned}
L_{ab} = L_{ba} &= -M_s - L_m \cos 2(\vartheta + \pi/6) \\
L_{bc} = L_{cb} &= -M_s - L_m \cos 2(\vartheta - \pi/2) \\
L_{ca} = L_{ac} &= -M_s - L_m \cos 2(\vartheta + 5\pi/6)
\end{aligned}
\tag{2.13}
$$

It should be noted that $\left| M_s \right| > L_m$.

- Rotor self-inductances

    The rotor self-inductances are constant and are given by,

$$
\begin{aligned}
L_{FF} &= L_F \\
L_{DD} &= L_D \\
L_{GG} &= L_G \\
L_{QQ} &= L_Q
\end{aligned}
\tag{2.14}
$$

- Rotor mutual inductances

$$
\begin{aligned}
L_{FD} = L_{DF} &= M_X \\
L_{GQ} = L_{QG} &= M_Y \\
L_{FG} = L_{GF} &= 0 \\
L_{FQ} = L_{QF} &= 0 \\
L_{DG} = L_{GD} &= 0 \\
L_{DQ} = L_{QD} &= 0
\end{aligned}
\tag{2.15}
$$

The rotor mutual inductances are constant for circuits that are located within the same axis, or zero for circuits that are located in different windings since the d and q axes are in quadrature.

- Stator-to-rotor mutual inductances

$$L_{aF} = L_{Fa} = M_F \cos \vartheta \qquad\qquad L_{aD} = L_{Da} = M_D \cos \vartheta$$
$$L_{bF} = L_{Fb} = M_F \cos(\vartheta - 2\pi/3) \qquad L_{bD} = L_{Db} = M_D \cos(\vartheta - 2\pi/3)$$
$$L_{cF} = L_{Fc} = M_F \cos(\vartheta + 2\pi/3) \qquad L_{cD} = L_{Dc} = M_D \cos(\vartheta + 2\pi/3)$$

$$L_{aG} = L_{Ga} = M_G \sin \vartheta \qquad\qquad L_{aQ} = L_{Qa} = M_Q \sin \vartheta$$
$$L_{bG} = L_{Gb} = M_G \sin(\vartheta - 2\pi/3) \qquad L_{bQ} = L_{Qb} = M_Q \sin(\vartheta - 2\pi/3)$$
$$L_{cG} = L_{Gc} = M_G \sin(\vartheta + 2\pi/3) \qquad L_{cQ} = L_{Qc} = M_Q \sin(\vartheta + 2\pi/3) \qquad (2.16)$$

It is observed that (2.11) has time-varying terms which will cause complication when their derivatives are taken. Thus, it is convenient to refer all quantities to a rotor frame of reference through a Park's transformation. The Park's transformation is only applied to the stator portion of the equation. To achieve this, (2.11) is premultiplied by

$\begin{bmatrix} P & 0 \\ 0 & U_4 \end{bmatrix}$, as shown in (2.17). P is the Park's transformation and U_4 is a 4×4 unit matrix,

$$\begin{bmatrix} P & 0 \\ 0 & U_4 \end{bmatrix}\begin{bmatrix} \lambda_{abc} \\ \lambda_{FDGQ} \end{bmatrix} = \begin{bmatrix} P & 0 \\ 0 & U_4 \end{bmatrix}\begin{bmatrix} L_{aa} & L_{aR} \\ L_{Ra} & L_{RR} \end{bmatrix}\begin{bmatrix} P^{-1} & 0 \\ 0 & U_4 \end{bmatrix}\begin{bmatrix} P & 0 \\ 0 & U_4 \end{bmatrix}\begin{bmatrix} i_{abc} \\ i_{FDGQ} \end{bmatrix}. \qquad (2.17)$$

The above operation results in,

$$\begin{bmatrix} \lambda_0 \\ \lambda_d \\ \lambda_q \\ \lambda_F \\ \lambda_D \\ \lambda_G \\ \lambda_Q \end{bmatrix} = \begin{bmatrix} L_0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & L_d & 0 & kM_F & kM_D & 0 & 0 \\ 0 & 0 & L_q & 0 & 0 & kM_G & kM_Q \\ 0 & kM_F & 0 & L_F & M_X & 0 & 0 \\ 0 & kM_D & 0 & M_X & L_D & 0 & 0 \\ 0 & 0 & kM_G & 0 & 0 & L_G & M_Y \\ 0 & 0 & kM_Q & 0 & 0 & M_Y & L_Q \end{bmatrix}\begin{bmatrix} i_0 \\ i_d \\ i_q \\ i_F \\ i_D \\ i_G \\ i_Q \end{bmatrix}, \qquad (2.18)$$

where $L_d = L_s + M_s + \dfrac{3}{2}L_m$, $L_q = L_s + M_s - \dfrac{3}{2}L_m$, $L_0 = L_s - 2M_s$, and $k = \sqrt{3/2}$.

Fig. 2.5 shows the schematic diagram of a synchronous generator assuming a representation of one damper winding in the direct axis and two damper windings in the quadrature axis. A neutral impedance to ground is also shown. Using matrix notation, the generator voltage equations become,

$$v = -ri - \lambda' - v_n,$$ (2.19)

where the neutral voltage contribution v_n is given by,

$$v_n = -r_n \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - L_n \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} i'_a \\ i'_b \\ i'_c \end{bmatrix}.$$ (2.20)

Equation (2.19) in its expanded form becomes,

$$\begin{bmatrix} v_a \\ v_b \\ v_c \\ -v_F \\ -v_D \\ -v_G \\ -v_Q \end{bmatrix} = - \begin{bmatrix} r_a & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & r_b & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & r_c & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & r_F & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & r_D & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & r_G & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & r_Q \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_F \\ i_D \\ i_G \\ i_Q \end{bmatrix} - \begin{bmatrix} \lambda'_a \\ \lambda'_b \\ \lambda'_c \\ \lambda'_F \\ \lambda'_D \\ \lambda'_G \\ \lambda'_Q \end{bmatrix} + \begin{bmatrix} v_n \\ 0 \end{bmatrix}.$$ (2.21)

In (2.21) the voltage is expressed in terms of both currents and flux linkages. This is not desirable and therefore one of the two variables has to be replaced. Equation (2.18) is employed to replace the flux linkage by the current variables. The choice of replacing the flux linkages rather than the currents is based on mainly two reasons. The main reason is that the available data from on-line measurements are voltage and current states. There will be no need to convert the currents into flux linkages in the above equation. The second reason is that the relationship between the voltages v_d and v_q and the state variables is much simpler than the one involving flux linkages.
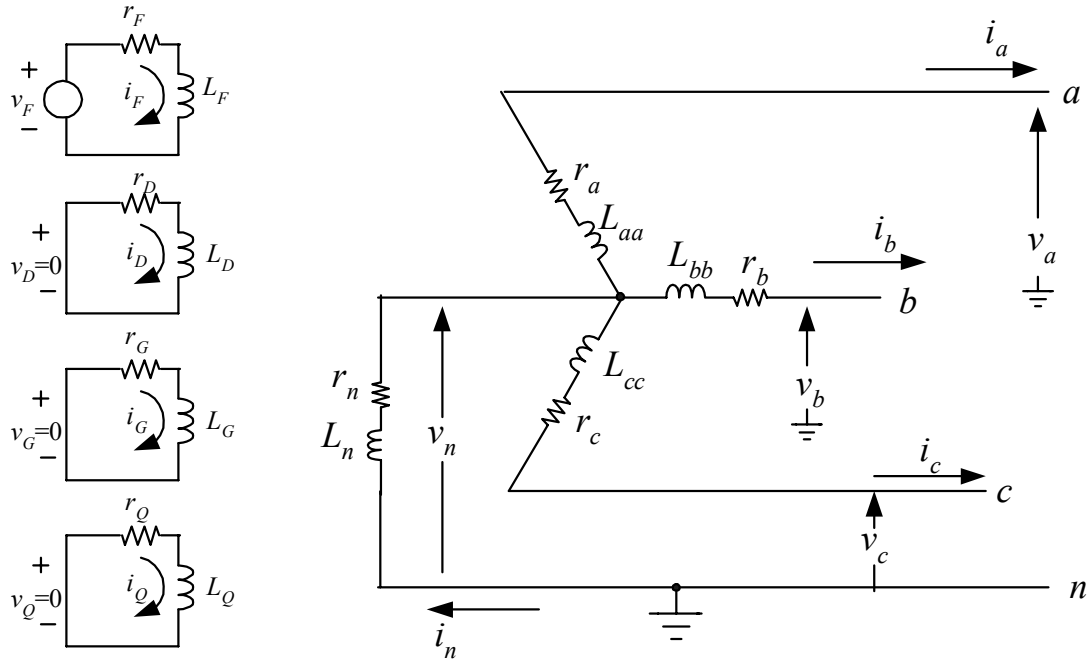
Fig. 2.5. Schematic diagram of a synchronous generator

Substituting all known parameters into (2.21), the mathematical model can be derived as,

$$
\begin{bmatrix} v_0 \\ v_d \\ v_q \\ -v_F \\ -v_D \\ -v_G \\ -v_Q \end{bmatrix} = -\begin{bmatrix} r+3r_n & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & r & \omega L_q & 0 & 0 & \omega kM_G & \omega kM_Q \\ 0 & -\omega L_d & r & -\omega kM_F & -\omega kM_D & 0 & 0 \\ 0 & 0 & 0 & r_F & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & r_D & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & r_G & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & r_Q \end{bmatrix}\begin{bmatrix} i_0 \\ i_d \\ i_q \\ i_F \\ i_D \\ i_G \\ i_Q \end{bmatrix}
$$

$$
-\begin{bmatrix} L_0+3L_n & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & L_d & 0 & kM_F & kM_D & 0 & 0 \\ 0 & 0 & L_q & 0 & 0 & kM_G & kM_Q \\ 0 & kM_F & 0 & L_F & M_X & 0 & 0 \\ 0 & kM_D & 0 & M_X & L_D & 0 & 0 \\ 0 & 0 & kM_G & 0 & 0 & L_G & M_Y \\ 0 & 0 & kM_Q & 0 & 0 & M_Y & L_Q \end{bmatrix}\begin{bmatrix} i_0' \\ i_d' \\ i_q' \\ i_F' \\ i_D' \\ i_G' \\ i_Q' \end{bmatrix}. \qquad (2.22)
$$

All quantities in (2.22) are in actual units. The per-unitized form of (2.22) will be considered in Chapter 3. Equation (2.22) effectively achieves to formulate the state variables (voltages and currents) in a form suitable for state estimation. The above equation can be easily rearranged in the form $Hx = z$, where x is a vector of the unknown parameters and H and z are a known matrix and vector respectively, provided that all the terms are linear. The only nonlinearity in the above equations derives from the presence of the synchronous speed ω. However, the synchronous speed does not vary significantly within the small intervals that are used during the estimation process because of the large time constants of synchronous generators. Therefore, (2.22) can safely be considered as linear.

Another interesting observation made from the above equation is that the zero sequence voltage is dependent only on i_0 and i_0'. In other words, it is decoupled from the remaining six equations and can be solved separately. The other equations are coupled in the form of a passive network except for the presence of the speed voltage terms. Finally, all elements in the matrices of the coefficients are constants with the exception of ω, which however, can be considered as a constant as explained previously.

CHAPTER 3

SATURATION OF SYNCHRONOUS GENERATOR INDUCTANCES

3.1 Introduction

As noted in Chapter 1, the operating parameters of generators change according to the operating conditions. This is mainly due to the magnetic saturation experienced by the generator inductances. Saturation is a phenomenon that becomes apparent when the current through an inductor exceeds a certain limit. In effect, saturation of an inductor occurs when the core of the inductor can no longer store magnetic energy.

An inductor is usually constructed using a ferromagnetic material such as iron or one of its alloys. A ferromagnetic material is composed of small domains whose dipole moments are randomly oriented. When the material is completely demagnetized, the net magnetic moment over the material is zero. As the current through the inductor increases (measured by means of the magnetic field intensity), the domains in the material tend to align in the direction of the magnetic field intensity. As more domains are aligned, the magnetic flux density increases. When all domains have aligned in the direction of the magnetic field intensity, the flux density reaches its saturation density and cannot increase further in the same fashion. As the magnetic field intensity increases beyond the saturation point, relatively small increases of the magnetic flux density occur. When a large number of magnetic domains align in this way, the material is said to be in its saturation region [93].

Saturation representation is critical in the correct modeling of synchronous machines. Reference [71] identifies saturation representation as the most important factor in the effort for improved synchronous machine models. The q axis reactance x_q is

the dominant factor in determining the rotor angle δ for a particular operating condition. The d axis reactance x_d is the dominant factor in determining the excitation voltage and the power/load angle characteristics. The margins of the steady state stability are calculated through knowledge of the power/load angle characteristics. Further, x_d plays an important role in the determination of the short circuit current [94]. Since both x_d and x_q are affected by saturation, it is necessary to model saturation so as to increase the reliability of the estimated parameters and benefit from such an estimation in improving the planning of the operation of synchronous machines.

The main effect of saturation in a synchronous generator is the decrease of its mutual inductances depending on the operating level of the generator. Such a decrease may be considerable as the generator is driven higher into saturation. Therefore, it is imperative that the effect of saturation be modeled in the parameter estimation procedure.

In general, the only available data for a synchronous generator are those obtained from the saturation curve of the machine and especially by the open circuit characteristic that is depicted on the saturation curve. An example of a typical saturation curve of a synchronous generator can be seen in Appendix B.1. The saturation curve is composed of three parts: the air gap line, the open circuit characteristic (OCC), and the short circuit characteristic (SCC). The SCC is a plot of the armature current versus the field current and is the rightmost straight line on the data sheet of the saturation curve as shown in Fig. B.1 of Appendix B. The SCC is not used for saturation calculations.

The air gap line and the OCC are plots of the field current required to overcome the reluctance of the air-gap, where the horizontal axis is the field current in units of

amperes and the vertical axis is the per unit armature voltage of the generator. The air gap line is tangent to the OCC and the deviation of the OCC from the air gap line indicates the degree of saturation of the generator inductances. Fig. 3.1 shows a sample saturation curve for a synchronous generator. This saturation curve will aid in analyzing the methodology that is followed for the consideration of saturation for synchronous generator inductances.

The representation of saturation is rather cumbersome because it is not possible to represent all the nonlinearities in a generator and the interaction between all the circuits within the stator and the rotor (including the fictitious windings) with any single model for all the operating conditions. Therefore, a number of assumptions have to be made in order to enable satisfactory modeling of saturation.
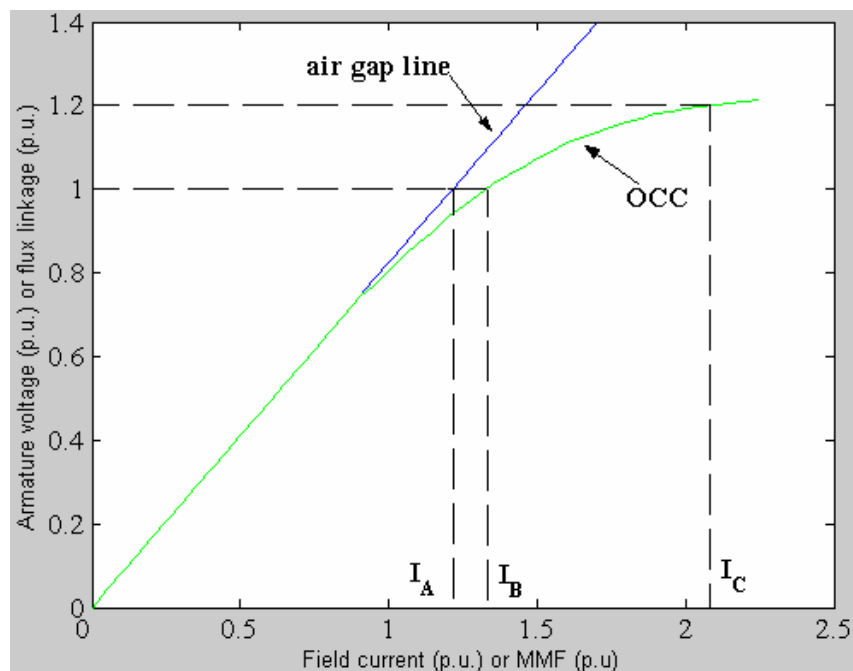
Fig. 3.1. Sample saturation curve for a synchronous generator

One of the major assumptions that needs to be made in the modeling of saturation is that only the mutual inductances L_{AD} and L_{AQ} saturate. L_{AD} and L_{AQ} appear in the model of the synchronous generator when (2.22) is transformed into its correct per unit form. This transformation will be considered in the next section. As far as the leakage inductances are concerned, these are assumed not to saturate since leakage fluxes are in air for a significant portion of their paths. Further, it is assumed that there is no magnetic coupling between the direct and quadrature axes because of saturation, and therefore no flux is produced that links one axis with the windings of the other axis. Finally, in order to be able to model saturation using the OCC, it is necessary to assume that the effect of saturation under loaded conditions is the same as under no load conditions [13]. In reality, the load saturation curve is not exactly the same as the OCC, but lies somewhat to the right of the OCC [95].

The effects of saturation for the mutual inductances L_{AD} and L_{AQ} may be represented by two saturation factors, one for each inductance [5], [13], [14]. The saturated inductances are given by,

$$L_{ADs} = K_{sd}L_{ADu}$$
$$L_{AQs} = K_{sq}L_{AQu} ,\qquad\qquad (3.1)$$

where K_{sd} and K_{sq} represent the saturation factors in each axis and the subscripts u and s refer to the unsaturated and saturated values of the inductance respectively. The two saturation factors represent the degree of saturation in the direct and quadrature axes. The saturation factors are in general not the same for both axes.

In the case of salient pole machines, K_{sq} is assumed to be unity for all loading conditions and thus L_{AQ} is considered a constant inductance [13], [14]. This is because the path for the quadrature axis flux is mainly in air and therefore the saturation experienced by L_{AQ} is insignificant. In the case of round rotor machines, saturation is significant in both the direct and quadrature axes. Both saturation factors need to be calculated from the d axis and q axis saturation curves. However, q axis saturation curves are typically not available and it is typically assumed that the q axis saturation factor is equal to the d axis saturation factor [13]. The assumption of equal saturation factors effectively assumes that the reluctance of the magnetic path is homogeneous around the periphery of the rotor [13]. The assumption of equal saturation effects also implies that the magnetic excitation in the direct and quadrature axes is equal.

For more accurate representation of saturation it is necessary to model the q axis saturation as well. For round rotor synchronous machines the q axis saturates appreciably more than the d axis because of the presence of rotor teeth in the magnetic path of the q axis [13]. All of the flux along the q axis passes through the rotor teeth and therefore, for the same amount of air gap flux density the teeth saturate more than the d axis. Further, saturation in the q axis occurs at a lower flux than saturation in the d axis [96].

References [72] and [97] describe saturation modeling in both the d and q axes by using finite element analysis. Finite element analysis is an accurate method of representing magnetic saturation, but the computational intensity of this method makes it impractical for on-line applications. References [74], [96], and [98]-[100], describe alternative methods to calculate the q axis saturation characteristic for both round rotor

and salient pole synchronous generators. The ideas discussed in [96] and [100] will be used in Section 3.3 to develop a model to estimate the q axis characteristic from the available d axis characteristic. Although the methodology used to derive the model is different from the one used in [96], the resulting models are identical for both methods.

Section 3.2 modifies (2.22) as derived in Chapter 2, to a per unit model that clearly shows the mutual inductances. The modified model enables an easier representation of saturation. Section 3.3 develops the methodology to estimate the q axis saturation curve from the available d axis saturation curve, while Section 3.4 shows how the saturation factors for both the d and q axes can be calculated and applied in the estimation procedure. Section 3.5 offers a list of the synchronous generators from which data sets have been used to evaluate the parameter estimation algorithm. These data sets have been obtained on-site through a digital fault recorder (DFR) at different operating points. A list of the data sets and the operating points at which they have been obtained is also offered in the same section. Section 3.6 offers a list of the case studies that are described in this dissertation.

3.2 Preparation of the generator model to account for saturation

In order to enable the implementation of the saturation model as discussed in the previous section, the generator model of (2.22) needs to be transformed in such a way so as to make the presence of the saturating inductances L_{AD} and L_{AQ} evident. This is achieved by selecting appropriate base quantities that link both the stator and the rotor

and converting the model into its per unit form. This section discusses the transformation of the model into the desired form.

Per unit conversion can also aid in the understanding of the method, simplify some of the expressions, and generalize the method to enable the estimation of parameters of any given synchronous generator. Moreover, the stator voltages are in the kilovolt range while the field quantities are often smaller; thus, per-unitization aids in the conceptual understanding of the magnitudes of all signals involved. Finally, conversion of the model into its per unit form enables the user to detect unrealistic values of the estimated parameters. If the rated power and voltage are taken as the base quantities, then the per unit values of the parameters of nearly all the generators under consideration will fall within a certain range of values.

The power and voltage bases selected for the stator are the respective rated quantities from the manufacturer stability study data sheet. The rotor base quantities need to be defined in accordance to the selection of the stator base quantities. Since both the stator and rotor windings are coupled electromagnetically, it is necessary to select the same time base in both circuits [91]. The choice of a common time base forces the base mutual inductance to be the geometric mean of the base self inductances [23]. Further, the power base of the rotor circuit is selected to be equal to the power base of the stator circuits. An analysis of the procedure for the selection of the bases for both the stator and rotor circuits and the calculation of generator parameters is offered in Appendix A.

The direct consequence of the selection of the same time base in the stator and rotor circuits is that the mutual inductances between circuits in the same axis (*d* and *q*

axes) are equal. Therefore, the following relationships expressed in per unit can be used to simplify the synchronous generator model of (2.22).

$$kM_F = kM_D = M_X = L_{AD}$$
$$kM_G = kM_Q = M_Y = L_{AQ}$$

$$(3.2)$$

L_{AD} and L_{AQ} are defined as the direct and quadrature axis magnetizing mutual inductances respectively. Further, the generator self inductances in both the direct and quadrature axes can be separated into two inductances: the mutual inductance and the leakage inductance. The direct axis self inductances are given by,

$$L_d = L_{AD} + \ell_d$$
$$L_F = L_{AD} + \ell_F$$
$$L_D = L_{AD} + \ell_D ,$$

$$(3.3)$$

while the quadrature axis self inductances are given by,

$$L_q = L_{AQ} + \ell_q$$
$$L_G = L_{AQ} + \ell_G$$
$$L_Q = L_{AQ} + \ell_Q ,$$

$$(3.4)$$

where ℓ_i denotes a leakage inductance for winding i.

Finally, it is needed to premultiply the second part of the equation of the model by the inverse of the rated frequency ω_B in order to obtain a dimensionally correct per unit form of the equation. The reason for this adjustment to the model can be shown in two ways. Consider the model equation in compact form. This is given by,

$$V_{actual} = -R_{actual} I_{actual} - L_{actual} I'_{actual} ,$$

$$(3.5)$$

where V, I, and I' are vectors, R and L are matrices and the subscript *actual* refers to the fact that the quantities in the vectors or matrices are actual quantities and not per unit.

Substituting each quantity with the product of its base and its per unit value, (3.5) becomes,

$$V_b V_{pu} = -R_b R_{pu} I_b I_{pu} - L_b L_{pu} I_b I'_{pu} .$$

(3.6)

Since $X = \omega L$ and $X_b = \dfrac{V_b}{I_b}$, the inductance base is given by,

$$L_b = \frac{V_b}{\omega_B I_b} .$$

(3.7)

Therefore, (3.6) becomes,

$$V_b V_{pu} = -R_b I_b R_{pu} I_{pu} - \frac{V_b}{\omega_B I_b} L_{pu} I_b I'_{pu} ,$$

(3.8)

which if simplified gives the desired per unit form,

$$V_{pu} = -R_{pu} I_{pu} - \frac{1}{\omega_B} L_{pu} I'_{pu} .$$

(3.9)

Alternatively, it can be argued that, since all quantities need to be expressed in per unit, it is necessary to express the time in per unit as well. The time component is present in the current derivative vector of (2.22). The time base (which is the same for both stator and rotor circuits as explained above), is given by the inverse of the rated frequency in radians per second, and therefore a current derivative in per unit should be written as,

$$\frac{\dfrac{di}{dt}}{t_B} ,$$

where i is in per unit and t_B is the time base in seconds. This can be rearranged as,

$$\frac{di}{dt\Big/t_B} = t_B\,\frac{di}{dt} = \frac{1}{\omega_B}\frac{di}{dt}\,. \tag{3.10}$$

Thus, the second part of the model equation that involves the derivatives of currents in the generator windings needs to be premultiplied by the inverse of the rated synchronous angular frequency. One could arguably develop a per unit base for inductance such that $V_L = L\dfrac{di}{dt}$ results in unit values for V_L, L, and $\dfrac{di}{dt}$, and this too would result in a factor of ω_B^{-1} as in (3.10).

Therefore, the synchronous generator model in per unit is given by,

$$\begin{bmatrix} v_0 \\ v_d \\ v_q \\ -v_F \\ -v_D \\ -v_G \\ -v_Q \end{bmatrix} = -\begin{bmatrix} r+3r_n & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & r & \omega(L_{AQ}+\ell_q) & 0 & 0 & \omega L_{AQ} & \omega L_{AQ} \\ 0 & -\omega(L_{AD}+\ell_d) & r & -\omega L_{AD} & -\omega L_{AD} & 0 & 0 \\ 0 & 0 & 0 & r_F & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & r_D & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & r_G & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & r_Q \end{bmatrix}\begin{bmatrix} i_0 \\ i_d \\ i_q \\ i_F \\ i_D \\ i_G \\ i_Q \end{bmatrix}$$

$$-\frac{1}{\omega_B}\begin{bmatrix} L_0+3L_n & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & L_{AD}+\ell_d & 0 & L_{AD} & L_{AD} & 0 & 0 \\ 0 & 0 & L_{AQ}+\ell_q & 0 & 0 & L_{AQ} & L_{AQ} \\ 0 & L_{AD} & 0 & L_{AD}+\ell_F & L_{AD} & 0 & 0 \\ 0 & L_{AD} & 0 & L_{AD} & L_{AD}+\ell_D & 0 & 0 \\ 0 & 0 & L_{AQ} & 0 & 0 & L_{AQ}+\ell_G & L_{AQ} \\ 0 & 0 & L_{AQ} & 0 & 0 & L_{AQ} & L_{AQ}+\ell_Q \end{bmatrix}\begin{bmatrix} i_0' \\ i_d' \\ i_q' \\ i_F' \\ i_D' \\ i_G' \\ i_Q' \end{bmatrix}, \tag{3.11}$$

where all quantities are in per unit except time which is in seconds and the base synchronous angular frequency which is in radians per second.

3.3 Derivation of flux equations for the *d* and *q* axes saturation

Typically, the only information that is available regarding saturation for synchronous generators is obtained from the manufacturer supplied *d* axis saturation curve. This information does not allow representation of saturation in the *q* axis of the machine. Fig. 3.2 shows a typical saturation characteristic for both the direct and quadrature axes. In this section a method will be shown to estimate the *q* axis open circuit characteristic from the available *d* axis characteristic. The resulting model is identical to the model proposed in [96], but the methodology used in this dissertation is different.
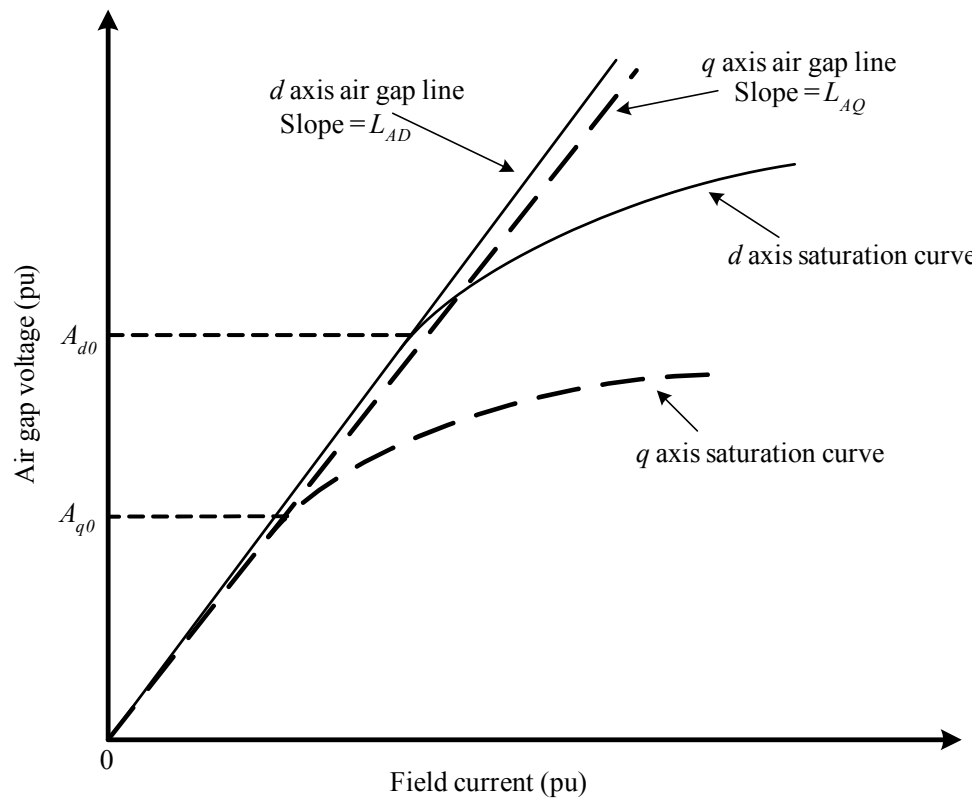
Fig. 3.2. Direct and quadrature axis characteristics

The effect of saturation can be related to the air gap flux density distribution. As can be observed from Fig. 3.2, an additional amount of magnetomotive force (MMF) or field current is required to overcome the reluctance of the air gap and to produce the same amount of flux that would be produced if saturation did not exist (i.e. if the air gap line represented higher values of field current as well as lower).

The air gap flux distribution Φ is given by,

$$\Phi(\vartheta) = F(\vartheta)P(\vartheta), \tag{3.12}$$

where $F(\vartheta)$ is the air gap MMF distribution, $P(\vartheta)$ is the air gap permeance distribution, and ϑ is the angular displacement from the center of the direct axis.

The flux produced by the stator winding follows a path that incorporates the stator iron, the air gap, and the rotor iron. Fig. 3.3 shows the variation of the permeance of this path as a function of rotor position. The permeance distribution can be approximated by,

$$P(\vartheta) = P_0 + P_2 \cos(2\vartheta), \tag{3.13}$$

where P_0 and P_2 are constants. The double frequency variation occurs because the permeances of the north and south poles are equal [13]. Some higher order even harmonics of permeance exist but they are negligible.

The MMF wave of phase a has a sinusoidal distribution about the rotor periphery and is given by,

$$MMF_a = Ki_a \cos\gamma, \tag{3.14}$$

where γ is the angle along the rotor periphery of the stator with respect to the center of phase a as shown in Fig. 3.4, i_a is the instantaneous current through the winding, and K is

a constant. The MMF waves produced by each phase are displaced 120 degrees apart. The MMF waves for phases *b* and *c* are given by,

$$MMF_b = Ki_b \cos(\gamma - \frac{2\pi}{3})$$

$$MMF_c = Ki_c \cos(\gamma + \frac{2\pi}{3}), \qquad (3.15)$$
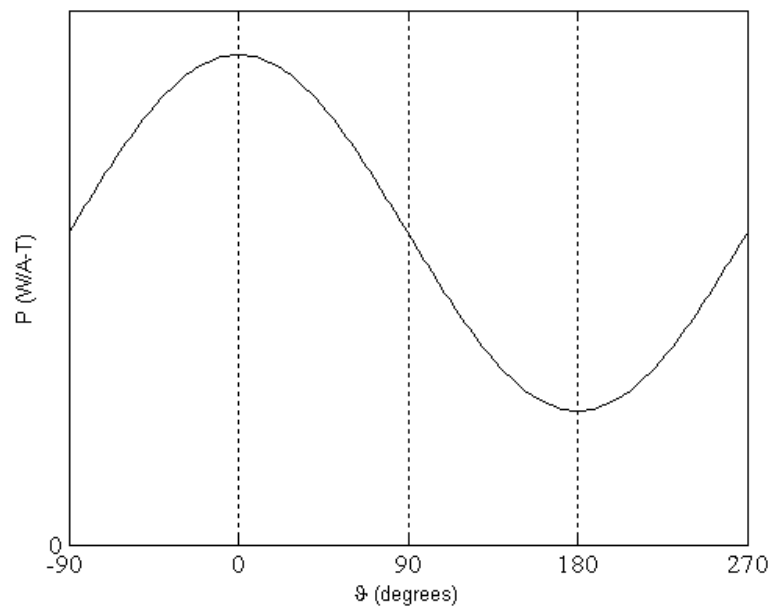
Fig. 3.3. Variation of permeance with rotor position

The MMF of phase *a* has a sinusoidal distribution in space (neglecting the space harmonics) with its peak centered on the axis of phase *a*. The peak amplitude of the MMF wave is equal to $N_a i_a$, where N_a is the effective turns per phase. Using the same principles as described in Chapter 2 with the use of Park's transformation, the peak MMF wave may be analyzed into two sinusoidally distributed components, one centered on the direct axis and the other on the quadrature axis. This is physically plausible since each

component acts on specific air gap geometry [13]. Fig. 3.5 shows the analysis of the MMF phasor into two components.

Phase *a* Phase *b* Phase *c*
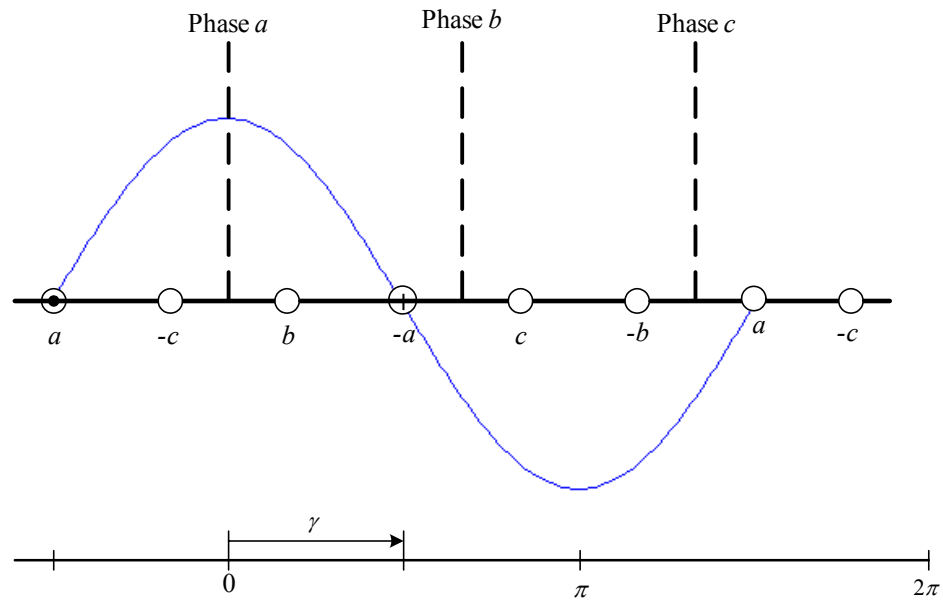
Fig. 3.4. MMF wave of phase *a* and angular displacement along the rotor periphery [13]
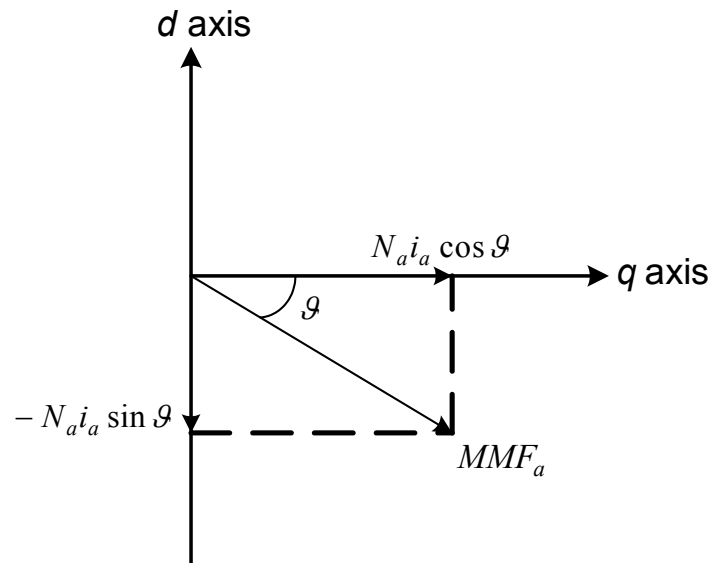
Fig. 3.5. Analysis of the MMF phasor into two sinusoidal components

Therefore the peak MMF in each axis is given by,

$$peak\ MMF_{AD} = N_a i_a \cos \vartheta$$
$$peak\ MMF_{AQ} = N_a i_a \sin \vartheta. \tag{3.16}$$

Substituting the variable AT to replace the ampere-turns product $N_a i_a$, the peak MMF in both axes is given by,

$$peak\ MMF = AT \cos(\vartheta - \alpha), \tag{3.17}$$

where $a = 0$ degrees for the d axis and $a = 90$ degrees for the q axis. In order to incorporate the effect of saturation, a component that describes the amount of extra MMF that is required to overcome the reluctance of the air gap in each axis is needed to be included in the model. Therefore, the peak MMF in any axis is given by,

$$peak\ MMF = AT \cos(\vartheta - \alpha) - \Delta AT, \tag{3.18}$$

where ΔAT is the saturation component of the flux. The saturation component is zero if there is no saturation. If the generator is operating in the saturation region, then this saturation component is a function of the flux density at the operating point. One way to represent the saturation component in each axis is,

$$\Delta AT_d = k(A_d - A_{d0})^2$$
$$\Delta AT_q = k(A_q - A_{q0})^2, \tag{3.19}$$

where A_d and A_q are the flux components of each axis at the operating point of the machine, A_{d0} and A_{q0} are the points where saturation starts in the d axis and q axis respectively, and k is a constant that depends on saturation.

Using (3.13) and (3.18), the flux distribution for each axis as defined in (3.12) can be expressed as,

$$\Phi_d(\vartheta) = [(AT\cos\vartheta - \Delta AT_d)\cos\vartheta][P_0 + P_2\cos(2\vartheta)]$$
$$\Phi_q(\vartheta) = [(AT\sin\vartheta - \Delta AT_q)\sin\vartheta][P_0 + P_2\cos(2\vartheta)]. \tag{3.20}$$

The average flux density in each axis can be obtained by taking the integral of each flux distribution through the period of each function.

The average flux density in the direct axis is given by,

$$A_d = \frac{2}{\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}[(AT\cos\vartheta - \Delta AT_d)\cos\vartheta][P_0 + P_2\cos(2\vartheta)]d\vartheta$$

$$= \frac{2}{\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}[ATP_0\cos^2\vartheta + ATP_2\cos^2\vartheta\cos 2\vartheta - \Delta AT_d P_0\cos\vartheta - \Delta AT_d P_2\cos\vartheta\cos 2\vartheta]d\vartheta$$

$$= \frac{2}{\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}[\frac{1}{2}ATP_0(1+\cos 2\vartheta) + \frac{1}{2}ATP_2(1+\cos 2\vartheta)\cos 2\vartheta - \Delta AT_d P_0\cos\vartheta$$

$$-\frac{1}{2}\Delta AT_d P_2(\cos\vartheta + \cos 3\vartheta)]d\vartheta$$

$$= \frac{2}{\pi}[\frac{1}{2}AT(P_0 + \frac{P_2}{2})\vartheta - \Delta AT_d(P_0 + \frac{P_2}{2})\sin\vartheta + \frac{1}{4}AT(P_0 + P_2)\sin 2\vartheta$$

$$-\frac{1}{6}\Delta AT_d P_2\sin 3\vartheta + \frac{1}{16}ATP_2\sin 4\vartheta]\Big|_{-\frac{\pi}{2}}^{\frac{\pi}{2}}$$

$$= AT(P_0 + \frac{P_2}{2}) - \frac{4}{\pi}\Delta AT_d(P_0 + \frac{P_2}{3}). \tag{3.21}$$

The flux distribution in the q axis is symmetric and therefore it is only necessary to integrate over half the period. The average flux density in the quadrature axis is thus given by,

$$A_q = \frac{2}{\pi} 2 \int_0^{\frac{\pi}{2}} [(AT \sin \vartheta - \Delta AT_q) \sin \vartheta][P_0 + P_2 \cos(2\vartheta)] d\vartheta$$

$$= \frac{4}{\pi} \int_0^{\frac{\pi}{2}} [ATP_0 \sin^2 \vartheta + ATP_2 \sin^2 \vartheta \cos 2\vartheta - \Delta AT_q P_0 \sin \vartheta - \Delta AT_q P_2 \sin \vartheta \cos 2\vartheta] d\vartheta$$

$$= \frac{4}{\pi} \int_0^{\frac{\pi}{2}} [\frac{1}{2} ATP_0 (1 - \cos 2\vartheta) + \frac{1}{2} ATP_2 (1 - \cos 2\vartheta) \cos 2\vartheta - \Delta AT_q P_0 \sin \vartheta$$

$$- \frac{1}{2} \Delta AT_q P_2 (-\sin \vartheta + \sin 3\vartheta)] d\vartheta$$

$$= \frac{4}{\pi} [\frac{1}{2} AT (P_0 - \frac{P_2}{2})\vartheta + \Delta AT_q (P_0 - \frac{P_2}{2}) \cos \vartheta - \frac{1}{4} AT (P_0 - P_2) \sin 2\vartheta$$

$$+ \frac{1}{6} \Delta AT_q P_2 \cos 3\vartheta - \frac{1}{16} ATP_2 \sin 4\vartheta]_0^{\frac{\pi}{2}}$$

$$= AT(P_0 - \frac{P_2}{2}) - \frac{4}{\pi} \Delta AT_q (P_0 - \frac{P_2}{3}). \tag{3.22}$$

Using (3.19), (3.21) and (3.22) are written as,

$$A_d = AT(P_0 + \frac{P_2}{2}) - \frac{4k}{\pi} (A_d - A_{d0})^2 (P_0 + \frac{P_2}{3}), \tag{3.23}$$

$$A_q = AT(P_0 - \frac{P_2}{2}) - \frac{4k}{\pi} (A_q - A_{q0})^2 (P_0 - \frac{P_2}{3}). \tag{3.24}$$

In order to estimate the q axis characteristic, the constants P_0, P_2, and k need to be determined for the generator under consideration. The constant k is zero if there is no saturation, and nonzero if the generator is operating in the saturation region. Considering the case where $k = 0$, (3.23) and (3.24) are simplified as,

$$A_d = AT(P_0 + \frac{P_2}{2}), \tag{3.25}$$

$$A_q = AT(P_0 - \frac{P_2}{2}), \tag{3.26}$$

and give the unsaturated (air gap) portion of the open circuit characteristic of the two axes. The slope of the air gap line in each axis is given by the mutual magnetizing inductance of each axis, and therefore for a characteristic that relates flux and ampere turns, (3.25) and (3.26) can be used to relate the mutual inductances to the constants P_0 and P_2.

$$\frac{A_d}{AT} = (P_0 + \frac{P_2}{2}) = X_{ADu} \tag{3.27}$$

$$\frac{A_q}{AT} = (P_0 - \frac{P_2}{2}) = X_{AQu} \tag{3.28}$$

Solving (3.27) and (3.28) for P_0 and P_2,

$$P_0 = \frac{(X_{ADu} + X_{AQu})}{2}, \tag{3.29}$$

$$P_2 = X_{ADu} - X_{AQu}. \tag{3.30}$$

Solving (3.23) for k, the value of k can be determined by the knowledge of a point on the d axis saturation characteristic. The value of k is given by,

$$k = [AT(P_0 + \frac{P_2}{2}) - A_d] \Big/ [\frac{4}{\pi}(A_d - A_{d0})^2(P_0 + \frac{P_2}{3})], \tag{3.31}$$

and can be used in (3.24) along with P_0 and P_2 to determine A_q for any value of AT and thus plot the q axis characteristic. Since A_{q0} is not known, it is estimated to be approximately half of A_{d0}. In other words, it is assumed that the q axis starts to saturate at half the flux that the d axis saturates. This is because the rotor teeth are in the magnetic path of the q axis and all of the flux passes through these teeth [13]. Therefore the density of the magnetic material in the q axis is approximately twice of that in the d axis, assuming equal rotor tooth and slot widths.

3.4 Implementation of saturation in the parameter estimation process

As noted in Section 3.1, the effects of saturation for the mutual inductances L_{AD} and L_{AQ} may be represented by two saturation factors as shown in (3.1) which is revisited below.

$$
\begin{aligned}
L_{ADs} &= K_{sd} L_{ADu} \\
L_{AQs} &= K_{sq} L_{AQu}
\end{aligned}
\tag{3.1}
$$

The saturation factors K_{sd} and K_{sq} relate the degree of saturation in each axis to the available saturation characteristics (either supplied from the manufacturer, or estimated). Therefore, a saturation function needs to be defined to simulate the actual saturation curve so as to enable calculation of the saturation factors at any operating point. A number of saturation functions have been proposed in the literature. Appendix C examines the accuracy of the proposed functions as well as other possible functions that can be used to model the saturation curve of a synchronous generator. From the results of Appendix C it is shown that an exponential function of the form,

$$
\lambda_I = \begin{cases} 0 & , \lambda_{at} \leq \lambda_0 \\ A_G e^{B_G(\lambda_{at} - \lambda_0)} & , \lambda_{at} > \lambda_0, \end{cases}
\tag{3.32}
$$

is the most suitable candidate from the proposed models to correctly duplicate the saturation curve provided by the manufacturer. λ_I is the flux linkage component required to overcome the reluctance of the air gap and is an indication of the degree of saturation, λ_{at} is the open circuit terminal flux linkage at the operating condition, and λ_0 is the assumed saturation threshold, which can be obtained from the saturation curve [14]. λ_0 is the per unit flux linkage at the point where the OCC deviates from the air-gap line. A_G and B_G are constants and they can be determined by the knowledge of two points on the

saturation curve. These points are usually the 1.0 p.u. and 1.2 p.u. terminal flux linkages as shown in Fig. 3.1.

To calculate A_G and B_G the value of the function at the two selected flux linkages (or terminal voltages) needs to be calculated first. From Fig. 3.1 at the two terminal voltages selected (1.0 p.u. and 1.2 p.u.), the values of λ_I are given by,

$$\lambda_{I1.0} = \frac{I_B - I_A}{I_A}$$

$$\lambda_{I1.2} = \frac{I_C - 1.2I_A}{1.2 \cdot I_A}. \tag{3.33}$$

Using (3.32) to solve for the constants A_G and B_G, it can be shown that [14],

$$A_G = \frac{\lambda^2{}_{I1.2}}{1.2\lambda_{I1.2}}$$

$$B_G = 5\ln\left(\frac{1.2\lambda_{I1.2}}{\lambda_{I1.0}}\right). \tag{3.34}$$

Using the values for A_G, B_G, and the saturation threshold λ_0, the saturation function λ_I can be calculated for any operating condition by calculating the terminal flux linkage λ_{at}.

The terminal flux linkage λ_{at} is given by,

$$\lambda_{at} = \sqrt{\lambda_{ad}^2 + \lambda_{aq}^2}, \tag{3.35}$$

where,

$$\lambda_{ad} = \lambda_d + x_l i_d = v_q + r i_q + x_l i_d$$
$$\lambda_{aq} = \lambda_q + x_l i_q = -v_d - r i_d + x_l i_q. \tag{3.36}$$

Alternatively,

$$\lambda_{at} = \left| E_t + (r + jx_l)I_t \right|, \tag{3.37}$$

where all quantities are in per unit.

The saturation factors for the direct and quadrature axes can then be calculated as,

$$K_{sd} = \frac{\lambda_{at}}{\lambda_{at} + \lambda_{Id}}$$

$$K_{sq} = \frac{\lambda_{at}}{\lambda_{at} + \lambda_{Iq}},$$ (3.38)

where λ_{Id} and λ_{Iq} are calculated from (3.32) for the d and q axis respectively, using the open circuit characteristics for each axis if they are both available. If the q axis characteristic is neither available nor can be estimated using a method such as in Section 3.3, then the saturation factor for the q axis can be assumed to be equal to the saturation factor for the d axis for a round rotor synchronous generator. The latter has been the approach that was used in the estimation of parameters from actual generator data as described in Chapter 8.

In the estimator implementation algorithm there are three different scenarios that need to be considered for the implementation of saturation. The first scenario involves the estimation of both L_{AD} and L_{AQ}, the second the estimation of one of the two parameters and the third the estimation of parameters other than the two mutual inductances. In the first two scenarios it is assumed that other parameters may or may not be estimated as well. There is no impact by the estimation of other parameters on the implementation of the saturation algorithm.

Considering the first scenario, estimating both mutual inductances does not require any implementation of the saturation algorithm within the estimator. The inductances that will be estimated are the saturated inductances at the operating point under consideration. The unsaturated inductances can then be calculated by performing

the inverse operation on the estimated saturated inductances. Therefore, the unsaturated inductances can be obtained by,

$$\hat{L}_{ADu} = \frac{\hat{L}_{AD}}{K_{sd}}$$

$$\hat{L}_{AQu} = \frac{\hat{L}_{AQ}}{K_{sq}}, \tag{3.39}$$

where ^ denotes an estimated quantity.

In the second scenario, if only one of the two inductances needs to be estimated, then it is necessary to adjust the other inductance for saturation prior to the estimation process in order to obtain the correct saturated value for the inductance to be estimated. The correction for saturation for the inductance that is not going to be estimated can be performed according to (3.1), while the unsaturated value for the estimated inductance can be obtained as in (3.39).

Finally, if none of the two inductances need to be estimated, then it is necessary to correct both for saturation prior to the implementation of the estimation algorithm. The saturated inductances are calculated using (3.1).

3.5 Description of generators studied and list of data sets used

This section offers an overview of the generators from which measurements have been obtained to test and verify the accuracy of the proposed method. Parameter estimation results using data sets from these generators are described in Chapter 8. Table 3.1 lists the generators, their location, and their characteristics. Table 3.2 lists the data

sets that have been used for the purposes of this dissertation and the associated case study

number.

TABLE 3.1

Generators studied and their characteristics

Generator name	Location	Type	Rated power (MVA)	Rated voltage (kV)	X_{ADu} (p.u.)	X_{AQu} (p.u.)	Manufacturer
FC4HP	Four Corners	Steam turbine	483	22	1.64	1.56	General Electric
FC5HP	Four Corners	Steam turbine	483	22	1.64	1.56	General Electric
GT1	Redhawk	Gas turbine	213.7	18	1.781	1.692	General Electric
GT2	Redhawk	Gas turbine	213.7	18	1.781	1.692	General Electric
ST1	Redhawk	Steam turbine	240	18	1.924	1.79	ALSTOM
ST2	Redhawk	Steam turbine	240	18	1.924	1.79	ALSTOM

TABLE 3.2

List of data sets obtained from actual measurements

Data set name	Corresponding generator	Case study no.	Operating point	
			Active power (MW)	Reactive power (MVAr)
FC5HP.dat	FC5HP	R-NC-01-10 R-NC-03-11 R-NC-03-12	142.2	-3.73
GT1A.dat	GT1	R-NC-03-13	148.4	13.26
GT1B.dat	GT1	R-NC-03-14	145.2	10.87
GT1ACase1.dat	GT1	R-NC-03-15	109.5	1.42
GT1ACase2.dat	GT1	R-NC-03-16	111.13	5.69
GT1ACase3.dat	GT1	R-NC-03-17	108.83	4.34
GT1ACase4.dat	GT1	R-NC-03-18	119.14	4.27
GT1ACase5.dat	GT1	R-NC-03-19	110.11	4.43
GT1ACase6.dat	GT1	R-NC-03-20	119.87	15.63
GT2A.dat	GT2	R-NC-03-21	109.1	9.03
GT2B.dat	GT2	R-NC-03-22	108.4	10.61
RedhawkST1.dat	ST1	R-NC-03-23	167.13	24.28
ST1Case1.dat	ST1	R-NC-03-24	123.91	6.90
ST1Case2.dat	ST1	R-NC-03-25	138.62	13.29
ST1Case3.dat	ST1	R-NC-03-26	61.34	4.19
ST1Case4.dat	ST2	R-NC-03-27	125.55	15.49
ST1Case5.dat	ST1	R-NC-03-28	140.35	11.25
ST1Case6.dat	ST1	R-NC-03-29	146.58	15.79
RedhawkST2.dat	ST2	R-NC-03-30	144.49	16.75

3.6 Denomination of case studies

This section explains the labeling of the case studies performed hereafter. This will enable the reader to follow the case studies in an easier manner and realize their use and purpose without having to refer to the manuscript. The numbering consists of four parts with a generic format of X-XX-XX-XX, where X represents the number of digits or letters in that part. The first part consists of one letter: S for synthetic data obtained by the numerical solution of the differential equations of the model, E for EMTP simulated data, or R for real data. The second part shows whether the case study was conducted with noisy data or whether it was noise free. The letters NF depict noise free measurements, while the letters NC depict noise contaminated measurements. The third and fourth parts are numeric and depict the number of parameters being estimated and the sequential number of the case study respectively.

For example, if a case study is conducted with synthetic data and without noise to estimate four parameters and this is the sixth study to be contacted in this research work, then it will be denoted as S-NF-04-06. If the next case study to be conducted is using real data with noise to calculate one parameter, it will be denoted as R-NC-01-07. Table 3.3 provides a summary of the case studies conducted for the purposes of this dissertation.

TABLE 3.3

List of case studies in the dissertation

Case study	Description	Section
E-NF-00-01	Observation of damper winding currents in steady state operation	4.4
E-NF-00-02	Observation of damper winding currents in transient operation	4.4
S-NF-03-03	Estimation of parameters for a small system with noise free measurements to determine the best minimization norm	5.3, 5.4
S-NC-03-04	Estimation of parameters for a small system with noisy measurements to determine the best minimization norm	5.3, 5.4
E-NF-01-05	Estimation of generator parameters from EMTP noise free data	6.3
E-NF-03-06	Multiple simultaneous estimation of generator parameters from EMTP noise free data using models 2.1 and 2.2	6.4
E-NF-03-07	Multiple simultaneous estimation of generator parameters from EMTP noise free data using models 2.1 and 2.2	6.4
E-NF-02-08	Multiple simultaneous estimation of generator parameters from EMTP noise free data using model 2.2x	6.4
E-NF-03-09	Multiple simultaneous estimation of generator parameters from EMTP noise free data using model 2.2x	6.4
R-NC-01-10	Estimation of parameters for generator FC5HP using actual data	8.2
R-NC-03-11	Multiple simultaneous estimation of generator parameters from actual measurements for generator FC5HP	8.3
R-NC-03-12	Multiple simultaneous estimation of generator parameters from actual measurements for generator FC5HP	8.3
R-NC-03-13	Estimation of parameters for generator GT1	8.4
R-NC-03-14	Estimation of parameters for generator GT1	8.4
R-NC-03-15	Estimation of parameters for generator GT1	8.4
R-NC-03-16	Estimation of parameters for generator GT1	8.4
R-NC-03-17	Estimation of parameters for generator GT1	8.4
R-NC-03-18	Estimation of parameters for generator GT1	8.4
R-NC-03-19	Estimation of parameters for generator GT1	8.4
R-NC-03-20	Estimation of parameters for generator GT1	8.4
R-NC-03-21	Estimation of parameters for generator GT2	8.4
R-NC-03-22	Estimation of parameters for generator GT2	8.4
S-NF-02-23	Parameter estimation for a sample system using noise free synthetic data to investigate the accuracy of various differentiation formulae	D.1
S-NC-02-24	Parameter estimation for a sample system using noisy synthetic data to investigate the accuracy of various differentiation formulae	D.1
R-NC-03-26	Estimation of parameters for generator ST1	F.1
R-NC-03-26	Estimation of parameters for generator ST1	F.1
R-NC-03-27	Estimation of parameters for generator ST1	F.1
R-NC-03-28	Estimation of parameters for generator ST1	F.1
R-NC-03-29	Estimation of parameters for generator ST1	F.1
R-NC-03-30	Estimation of parameters for generator ST1	F.1
R-NC-03-31	Estimation of parameters for generator ST1	F.1
R-NC-03-32	Estimation of parameters for generator ST2	F.1

3.7 Summary

This chapter described the need for correct representation of magnetic saturation in synchronous generators. Further, it is necessary to represent saturation in both the direct and quadrature axes for more accurate modeling. A method to estimate the q axis saturation curve from the available d axis saturation curve was shown. The results shown in this dissertation correspond to the representation of saturation using equal saturation factors in both axes.

The synchronous generator model was modified to enable easier implementation of saturation. The calculation of saturation factors was demonstrated in Section 3.4. Finally, Sections 3.5 and 3.6 offer a list of the generators studied for the purposes of testing the developed algorithm, and the associated case studies.

CHAPTER 4

DEVELOPMENT OF AN OBSERVER FOR THE DAMPER WINDING CURRENTS

4.1 Introduction

The synchronous generator model that was developed in Chapter 2 and the subsequent per unit model of Chapter 3 essentially formulates a multiple input-multiple output (MIMO) system. The system is formed in a state equation of the form,

$$V = -RI - LI',$$ (4.1)

where the matrices R and L contain parameters of the generator that are either known or desired to be estimated, and the vectors $V, I,$ and I' contain the voltages and currents that are assumed to be measured directly from the generator terminals.

Equation (3.11), which is revisited below,

$$
\begin{bmatrix} v_0 \\ v_d \\ v_q \\ -v_F \\ -v_D \\ -v_G \\ -v_Q \end{bmatrix} = -
\begin{bmatrix}
r+3r_n & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & r & \omega(L_{AQ}+\ell_q) & 0 & 0 & \omega L_{AQ} & \omega L_{AQ} \\
0 & -\omega(L_{AD}+\ell_d) & r & -\omega L_{AD} & -\omega L_{AD} & 0 & 0 \\
0 & 0 & 0 & r_F & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & r_D & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & r_G & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & r_Q
\end{bmatrix}
\begin{bmatrix} i_0 \\ i_d \\ i_q \\ i_F \\ i_D \\ i_G \\ i_Q \end{bmatrix}
$$
$$
-\frac{1}{\omega_B}
\begin{bmatrix}
L_0+3L_n & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & L_{AD}+\ell_d & 0 & L_{AD} & L_{AD} & 0 & 0 \\
0 & 0 & L_{AQ}+\ell_q & 0 & 0 & L_{AQ} & L_{AQ} \\
0 & L_{AD} & 0 & L_{AD}+\ell_F & L_{AD} & 0 & 0 \\
0 & L_{AD} & 0 & L_{AD} & L_{AD}+\ell_D & 0 & 0 \\
0 & 0 & L_{AQ} & 0 & 0 & L_{AQ}+\ell_G & L_{AQ} \\
0 & 0 & L_{AQ} & 0 & 0 & L_{AQ} & L_{AQ}+\ell_Q
\end{bmatrix}
\begin{bmatrix} i'_0 \\ i'_d \\ i'_q \\ i'_F \\ i'_D \\ i'_G \\ i'_Q \end{bmatrix},
$$ (3.11)

is the full matrix equation of the model of the synchronous generator. An examination of the voltage and current vectors shows that the last three equations of the model involve the voltage across and the current through each one of the three damper windings $D, G,$ and Q. Damper (amortisseur) windings form one of the most important factors for

damping in power systems. The action of damper windings is very crucial to the operation of electrical generators and to the stability of the power system as a whole.

In the case of salient pole generators, damper windings consist of metal bars placed in slots in the pole faces and connected together at each end. These bars can be connected together via a closed ring on both sides of the pole. In this case, they are called complete or connected damper windings. It is also possible for these bars not to be connected in between the poles, but each pole to have its own independent set of metal bars. In this case, the damper windings are known as incomplete, non-connected, or open windings [101].

In the case of round rotor generators (steam and gas turbines), their rotors are made up of solid steel forgings [13]. These generators do not usually have damper windings but the solid steel rotor core provides a path for eddy currents. The eddy currents in the rotor path produce the same effect as damper windings. In some cases, certain manufacturers provide for additional damping effects and negative sequence braking by using interconnected metal wedges in the field winding slots or by providing separate copper rods underneath the wedges [13].

There are several reasons for providing damper windings for synchronous machines. Damper windings provide starting torque for synchronous motors, condensers, and converters, and are used to suppress hunting. Hunting is the damped mechanical oscillation of the rotor about its new steady state angle after the mechanical speed of the rotor has changed [24]. The suppression of hunting has been the first application of the damper windings.

Further, damper windings are used to damp oscillations that are started by switching or faults. The existence of damper windings causes the oscillations to damp out faster. In the case of asymmetrical faults, the damper currents provide a braking torque and therefore the accelerating torque is reduced during the fault. Another important application of damper windings is the balancing of the terminal voltage of each phase during unbalanced loading. Damper windings decrease the negative sequence reactance and therefore they decrease the negative sequence voltage [101].

Additionally, during current surges in the armature circuit (in case of internal faults), the damper windings reduce the stress on the insulation of the field winding by the induced flux through the windings. Finally, the damper windings provide additional torque for synchronizing generators. They help to pull the generator back into step after synchronism is lost because of a fault [101].

In the case of the voltages in (3.11), all damper winding voltages v_D, v_G, and v_Q are zero since there is no voltage source in the damper windings. In the case of a doubly excited synchronous generator the model of (3.11) can still describe the synchronous machine but v_G will not be zero. As previously indicated, damper currents are zero (or very small) in the steady state operation of the synchronous generator, and nonzero during transients. However, it is not possible to measure the damper currents directly using physical instruments - even in the case that the damper windings are not fictitious. Therefore, it is necessary to estimate the damper currents by means of an *observer* prior to the implementation of the state estimator for the generator parameters.

4.2 Observers and observability

In general, a linear system may be represented in a state space realization of the form,

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t),\end{aligned} \qquad\qquad (4.2)$$

where $x(t) \in \Re^n$ is the vector of the states of the system, $u(t) \in \Re^m$ is the input to the system, and $y(t) \in \Re^p$ is the output of the system. For the purposes of the observer design, $A \in \Re^{nxn}$, $B \in \Re^{nxm}$, $C \in \Re^{pxn}$, and $D \in \Re^{pxm}$ must be time invariant and known except in the case of adaptive observers, where it is possible to estimate both the states and some of the parameters of the system simultaneously.

Observers are dynamic systems that use current and past values of the plant input, output, and known states to generate an estimate of the unknown (unmeasurable) states. The plant parameters need to be known and the plant should be observable. A simple test for observability is the requirement that the subsystem of (4.2) described by (*A, C*) has full column rank [102]-[105]. The synchronous generator model of (3.11) can be shown to be observable.

Various observer configurations have been proposed in the literature and are mainly categorized into open loop observers and closed loop observers. Open loop observers are simple in construction, but since the complete dynamics of the plant are rarely known exactly, no control is provided over the error generated by the observer [67]. A general open loop observer is shown in Fig. 4.1.
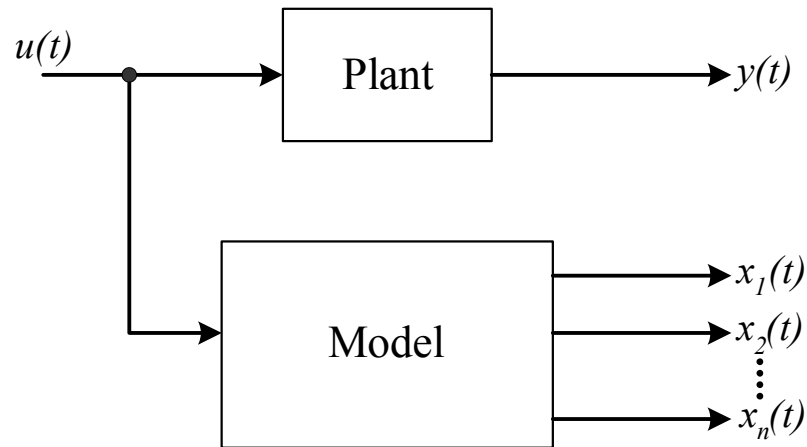
Fig. 4.1. Open loop observer

An improvement over the open loop observer is the closed loop observer. A schematic diagram of such an observer is shown in Fig. 4.2. An error signal between the plant and the observer is generated, and control over the state error can be achieved. Appropriate selection of the eigenvalues of the (A-LC) matrix can cause the error to go to zero at a relatively short time.

The concept of an observer for a dynamic process was introduced by Luenberger in 1966 [69]. Luenberger recognized that often the full state vector of a system is not available, either because there is no access to all the states or because the instrumentation required to measure all the states is very expensive. Therefore, it is desired to obtain an approximation of the unavailable states so as to enable the design of feedback or other control laws even in cases where the entire state vector is unknown.

Plant

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned}$$

$u(t)$

$y(t)$

Observer

$$\begin{aligned} \dot{\hat{x}}(t) &= A\hat{x}(t) + Bu(t) \\ \hat{y}(t) &= C\hat{x}(t) + Du(t) \end{aligned}$$

$\hat{x}(t)$

$\hat{y}(t)$

L
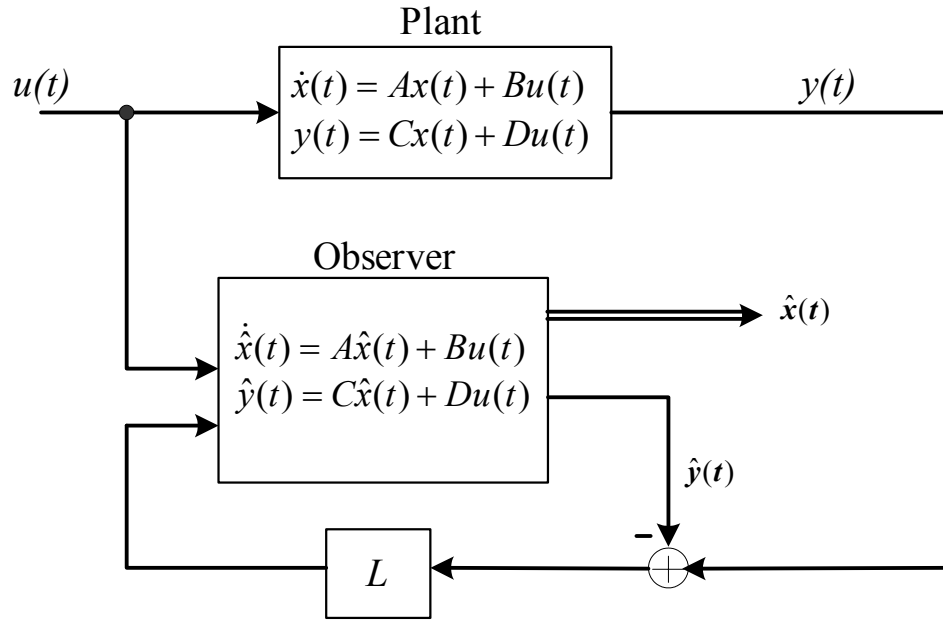
Fig. 4.2. Closed loop observer

One of the variations of the Luenberger observer is the identity observer [68], [70]. Let the system under consideration be of the form,

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) , \end{aligned} \tag{4.3}$$

where all the matrices are as defined in (4.2) and are time-invariant and known. The system is assumed to be *n* dimensional and the output vector to be *p* dimensional. It is also necessary for the system to be completely observable. The identity observer is of the form,

$$\dot{z}(t) = Az(t) + E[y(t) - Cz(t)] + Bu(t) , \tag{4.4}$$

where $E \in \Re^{nxp}$, and is selected so that the eigenvalues of *A-EC* have negative real parts so that the error is reduced to zero in a finite time.

The error tends to zero at a rate determined by the dominant eigenvalue of *A-EC*, and the state of the observer will converge to the state of the observed system. A good practice is to select the eigenvalues of *A-EC* to be more negative than the eigenvalues of the observed system so that the convergence is fast enough. However, the eigenvalues cannot be moved arbitrarily towards minus infinity, since that will force the observer to act like a differentiator and be extremely sensitive to noise [70]. An identity observer is shown in Fig. 4.3. The identity observer estimates the whole state vector.
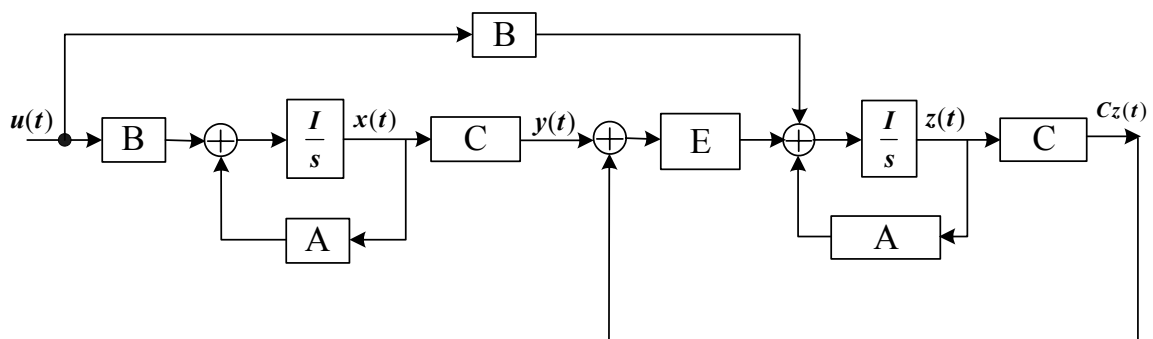
Fig. 4.3. Luenberger identity observer for a linear system

An improvement over the identity observer is the reduced order observer. Since usually some of the states are measurable, it is possible to construct an observer of order *n-p* rather than *n* (*p* are the measured states and *n* is the dimension of the full state). This provides better performance and uses a dynamic system of lower dimension, which improves the speed of the observation.

An example of such an observer can be seen in Fig. 4.4. As before, the system matrices need to be time invariant and known. Assuming the system is of the form of

(4.3), it is possible to apply a transformation T to the state vector so that the new state vector becomes,

$$\bar{x}(t) = Tx(t)$$
$$T = \begin{bmatrix} V \\ C \end{bmatrix},$$

(4.4)

where V is selected so that T is nonsingular. The new state vector can then be partitioned as,

$$\bar{x}(t) = \begin{bmatrix} w(t) \\ y(t) \end{bmatrix}.$$

(4.5)

This is because,

$$y(t) = Cx(t).$$

(4.6)

The vector $w(t)$ is now an n-p dimensional vector which is desired to be estimated.

In partitioned form, the system under consideration becomes,

$$\begin{bmatrix} \dot{w}(t) \\ \dot{y}(t) \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} w(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} u(t).$$

(4.7)

Multiplying the bottom part of (4.7) by an arbitrary matrix $E \in \mathfrak{R}^{(n-p) \times p}$, and subtracting from the top part,

$$\dot{w}(t) - E\dot{y}(t) = (A_{11} - EA_{21})[w(t) - Ey(t)] + (A_{11}E - EA_{21}E + A_{12} - EA_{22})y(t)$$
$$+ (B_1 - EB_2)u(t).$$

(4.8)

Using $z(t) = w(t) - Ey(t)$,

$$\dot{z}(t) = (A_{11} - EA_{21})z(t) + (A_{11}E - EA_{21}E + A_{12} - EA_{22})y(t) + (B_1 - EB_2)u(t).$$

(4.9)

From the state $z(t)$ of the observer, the original state of (4.7) can be estimated as,

$$\hat{w}(t) = z(t) + Ey(t)$$
$$\hat{y}(t) = y(t). \tag{4.10}$$

Using these two estimated vectors, an approximation to the state of the original system is thus constructed.
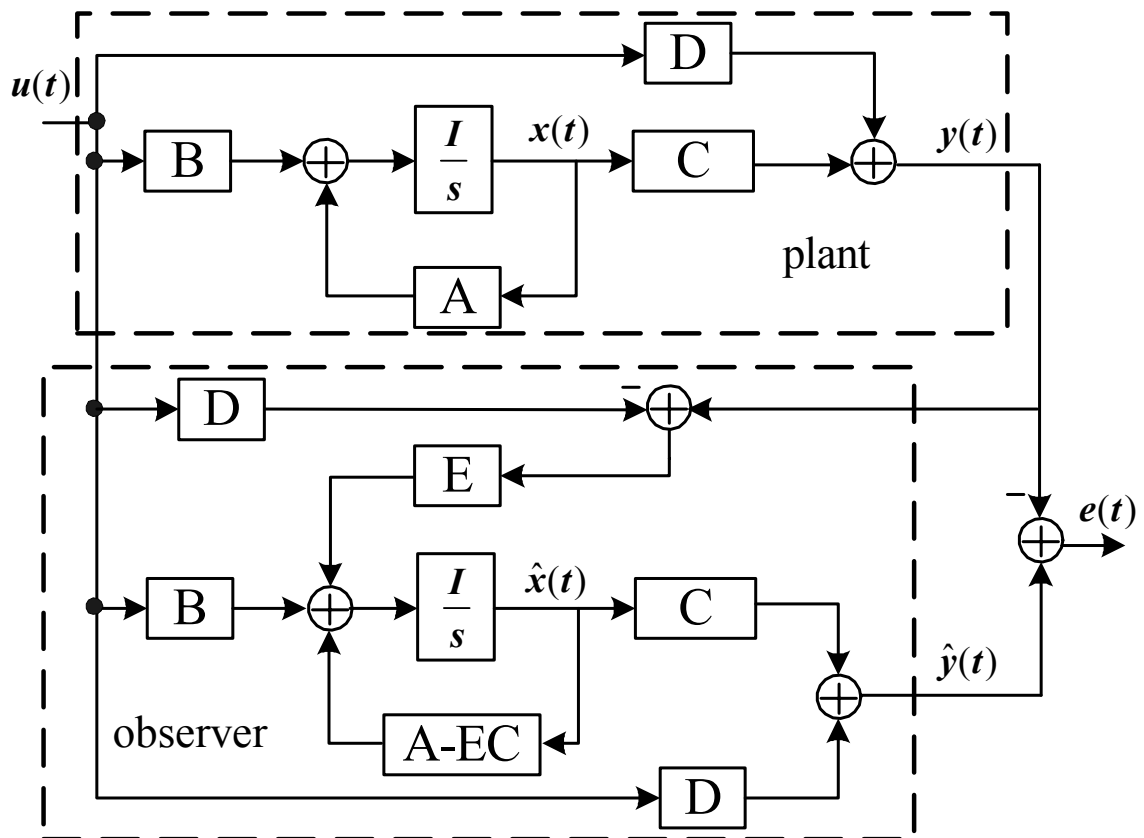
Fig. 4.4. Luenberger observer for a linear system [102]

Luenberger observers have the advantage that they are simple to construct and cheap. They can be simplified to a reduced dimension observer so as not to estimate the whole state vector if it is already available. Luenberger observers can be employed within many modern control strategies and are applicable to both continuous and discrete

systems. Finally, if they are well designed, they do not suffer from noise amplification and are ideal for applications where the model of the system is well known.

On the other hand, if the model is not well known, the reduced order Luenberger observer will not perform as desired. The identity observer will offer better results, but still the uncertainty that always exists in the parameters will cause some errors in the observation. Also, care must be taken in the selection of matrix E that specifies the rate of convergence of the estimation. If the eigenvalues of A-EC are very small (towards minus infinity), the observer will act as a differentiator and the system noise will be amplified. Finally, Luenberger observers cannot be applied in case A, B, C, and D are not completely known and time invariant.

4.3 Observer design

Usually, available data for synchronous generators are the stator phase currents and voltages at the terminals of the machine, and the field voltage and current. As stated in Section 4.1, in order to formulate the parameter estimation problem, it is necessary to have measurements for the damper currents i_D, i_G, and i_Q.

The conventional observer configurations that are reported in the literature and were described in Section 4.2, transform the system model in the form,

$$\dot{x} = Ax + Bu \,, \tag{4.11}$$

which can easily be realized by a block diagram. Nevertheless, transformation of the system into an observable canonical form as above, leads to a system that is nonlinear in the parameters. This is because the system under consideration is of the form,

$$V = -RI - LI' , \tag{4.12}$$

which if rearranged in the same form as (4.11) becomes,

$$I' = -L^{-1}RI - L^{-1}V . \tag{4.13}$$

Hence, both the matrix inverse and the matrix product in (4.13) will contain the product of two or more parameters which are desired to be estimated, thus forming a nonlinear system. It is likely that the parameters that occur in a product will not be possible to be separated in an estimation process except using linearization. Linearization will introduce a finite amount of error and will render the estimation process more complex. Finally, a requirement for the design of an observer using (4.11) and one of the available methods such as the Luenberger observer, is that the initial conditions of the system are known. In this case, the initial conditions are not known since the damper winding currents are unmeasurable.

Considering the difficulties for the implementation of a "standard" observer, it is desired to construct an "abstract" observer based on the existing knowledge about the system. The observer should be able to construct estimates of the damper winding currents by using voltage and current measurements from the system and *a priori* system knowledge. The observer should be designed in such a way so as to be effectively utilized by the parameter identification algorithm as shown in Fig. 4.5.

For the construction of the observer, the last three equations of the synchronous generator model in (3.11) can be rearranged so as to obtain expressions for the damper winding currents. The three equations are given by,

$$-v_D = 0 = -r_D i_D - \frac{1}{\omega_B} L_{AD} i'_d - \frac{1}{\omega_B} L_{AD} i'_F - \frac{1}{\omega_B}(L_{AD} + \ell_D) i'_D \tag{4.14}$$

$$-v_G = 0 = -r_G i_G - \frac{1}{\omega_B} L_{AQ} i'_q - \frac{1}{\omega_B}(L_{AQ} + \ell_G) i'_G - \frac{1}{\omega_B} L_{AQ} i'_Q \tag{4.15}$$

$$-v_Q = 0 = -r_Q i_Q - \frac{1}{\omega_B} L_{AQ} i'_q - \frac{1}{\omega_B} L_{AQ} i'_G - \frac{1}{\omega_B}(L_{AQ} + \ell_Q) i'_Q, \tag{4.16}$$

where for the purposes of the development of the observer the current derivatives will be

replaced by the forward difference formula,

$$i'(t) \approx \frac{i(t + \Delta t) - i(t)}{\Delta t}. \tag{4.17}$$

A discussion for the selection of (4.17) as the numerical approximation of the derivative

is offered in Section 5.5 and Appendix D.
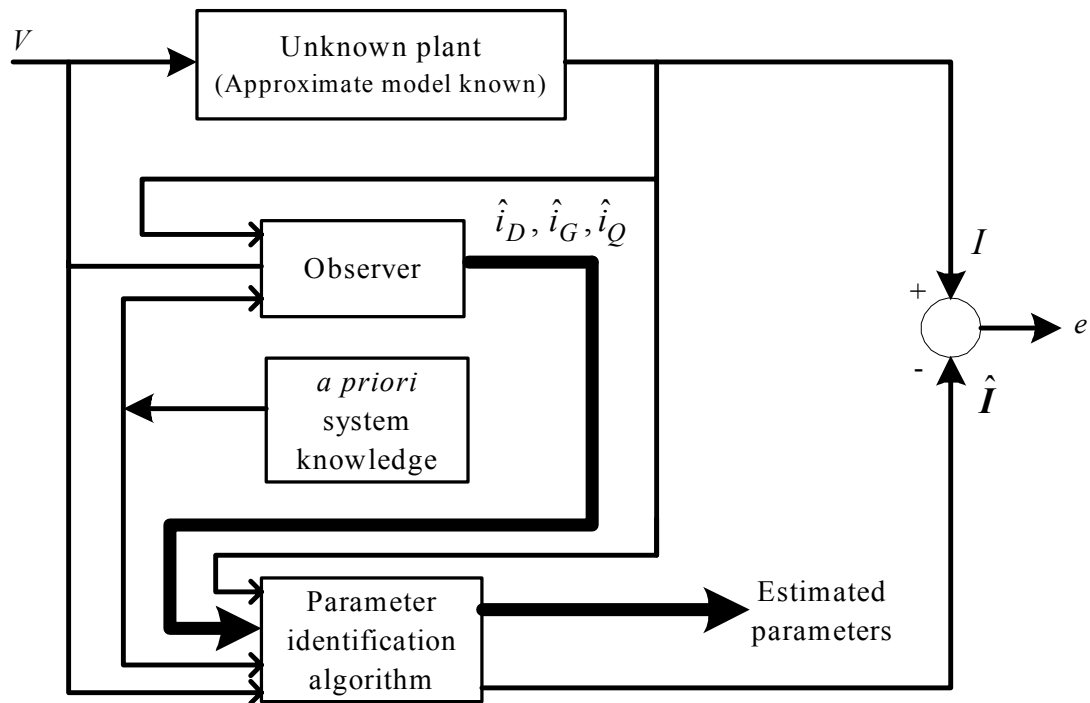
Fig. 4.5. Observer implementation and parameter identification algorithm

Using (4.17) for the damper current i_D, and writing (4.14) in discrete form,

$$0 = r_D i_D(n) + \frac{1}{\omega_B} L_{AD}(i_d'(n) + i_F'(n)) + \frac{1}{\omega_B}(L_{AD} + \ell_D)(\frac{i_D(n+1) - i_D(n)}{\Delta t}) . \qquad (4.18)$$

Solving for $i_D(n+1)$, an expression can be obtained in terms of known measurements and

the previously calculated value of i_D. The damper current i_D can thus be obtained by,

$$i_D(n+1) = (1 - \frac{r_D \omega_B \Delta t}{L_{AD} + \ell_D}) i_D(n) - \frac{L_{AD} \Delta t}{L_{AD} + \ell_D}(i_d'(n) + i_F'(n)) . \qquad (4.19)$$

The quadrature axis damper winding currents i_G and i_Q can be obtained by the

simultaneous solution of (4.15) and (4.16) as shown in the following development.

Solving (4.15) for $i_G(n+1)$,

$$0 = r_G i_G(n) + \frac{1}{\omega_B} L_{AQ} i_q'(n) + \frac{1}{\omega_B}(L_{AQ} + \ell_G)(\frac{i_G(n+1) - i_G(n)}{\Delta t}) + \frac{1}{\omega_B} L_{AQ}(\frac{i_Q(n+1) - i_Q(n)}{\Delta t})$$

$$\Rightarrow i_G(n+1) = (1 - \frac{r_G \omega_B \Delta t}{L_{AQ} + \ell_G}) i_G(n) - \frac{L_{AQ}}{L_{AQ} + \ell_G} i_Q(n+1) + \frac{L_{AQ}}{L_{AQ} + \ell_G} i_Q(n) - \frac{L_{AQ} \Delta t}{L_{AQ} + \ell_G} i_q'(n) \quad (4.20)$$

Similarly, solving (4.16) for $i_Q(n+1)$,

$$0 = r_Q i_Q(n) + \frac{1}{\omega_B} L_{AQ} i_q'(n) + \frac{1}{\omega_B} L_{AQ}(\frac{i_G(n+1) - i_G(n)}{\Delta t}) + \frac{1}{\omega_B}(L_{AQ} + \ell_q)(\frac{i_Q(n+1) - i_Q(n)}{\Delta t})$$

$$\Rightarrow i_Q(n+1) = (1 - \frac{r_Q \omega_B \Delta t}{L_{AQ} + \ell_Q}) i_Q(n) - \frac{L_{AQ}}{L_{AQ} + \ell_Q} i_G(n+1) + \frac{L_{AQ}}{L_{AQ} + \ell_Q} i_G(n) - \frac{L_{AQ} \Delta t}{L_{AQ} + \ell_Q} i_q'(n) \quad (4.21)$$

Substituting (4.20) into (4.21) the damper current in the Q winding can be obtained as,

$$i_Q(n+1) = \left[1 - \frac{(L_{AQ} + \ell_G) r_Q \omega_B \Delta t}{(L_{AQ} + \ell_Q)(L_{AQ} + \ell_G) - L_{AQ}^2}\right] i_Q(n) + \left[\frac{L_{AQ} r_G \omega_B \Delta t}{(L_{AQ} + \ell_Q)(L_{AQ} + \ell_G) - L_{AQ}^2}\right] i_G(n)$$

$$- \left[\frac{L_{AQ} \ell_G \Delta t}{(L_{AQ} + \ell_Q)(L_{AQ} + \ell_G) - L_{AQ}^2}\right] i_q'(n). \qquad (4.22)$$

Finally, substituting (4.22) into (4.20) the damper current in the G winding can be

obtained as,

$$i_G(n+1) = \left[1 - \frac{(L_{AQ} + \ell_Q)r_G\omega_B\Delta t}{(L_{AQ} + \ell_Q)(L_{AQ} + \ell_G) - L_{AQ}^2}\right]i_G(n) + \left[\frac{L_{AQ}r_Q\omega_B\Delta t}{(L_{AQ} + \ell_Q)(L_{AQ} + \ell_G) - L_{AQ}^2}\right]i_Q(n)$$

$$+ \frac{L_{AQ}\Delta t}{(L_{AQ} + \ell_G)}\left[\frac{L_{AQ}\ell_G}{(L_{AQ} + \ell_Q)(L_{AQ} + \ell_G) - L_{AQ}^2} - 1\right]i_q'(n). \tag{4.23}$$

Equations (4.19), (4.22), and (4.23) constitute the observer for the estimation of the damper winding currents. The damper currents at each step are expressed in terms of generator parameters, known measurements of stator and rotor currents, as well as estimates of the damper currents at the previous time step. The generator parameters involved in the three observer equations are mainly parameters of damper windings, which can be readily calculated from manufacturer data as shown in Appendix A. Two of the parameters that occur in the observer equations are parameters that are usually desired to be estimated. These parameters are the magnetizing inductances L_{AD} and L_{AQ}. Nevertheless, these inductances can be calculated approximately from the manufacturer data sheet without inhibiting the correct operation of the observer. The case studies that will be described in the next section lead to errors in the damper currents that are very low. If magnetizing inductances of a magnitude that differs by 10% is used in the observer, the error magnitudes in the damper currents do not increase by more than 0.5%. This behavior is observed in more than one test case and thus it can safely be concluded that the observer operation is not sensitive to changes in L_{AD} and L_{AQ} (for example, if saturation is not considered during the observer implementation).

Another point of ambiguity in the observer equations is the value that needs to be assigned to the initial conditions $i_D(0)$, $i_G(0)$, and $i_Q(0)$. The initial conditions are needed to initiate the observation process. As the case studies will demonstrate in the

next section, the initial conditions can be assumed to be zero without loss of accuracy in the damper currents. Assigning zero initial conditions when these are not available generates estimates that are suboptimal [82].

4.4 Verification of observer operation using EMTP simulated data

Since damper winding currents are not measurable in actual generators, it is not possible to determine the validity of the observer using actual measurements from field tests. Therefore, it is necessary to test the observer using measurements generated by well known and well tested simulation programs such as the Electromagnetic Transients Program (EMTP). EMTP is extensively used by utilities to simulate the behavior of synchronous generators and power systems in general, in both steady state and transient operation. Data from the EMTP simulation are free of noise and one has access to all generator parameters and signals. Furthermore, EMTP provides the simulated damper currents in the direct and quadrature axes. Possible agreement of the observer generated damper currents with the EMTP generated damper currents will increase the confidence in using the generated signals from the observer into the parameter estimation process. The synchronous generator under consideration as described in Appendix A was simulated using EMTP both in the steady state and in the transient mode.

In the first case study (E-NF-00-01), the machine is operating in steady state. The damper winding currents are observed according to the observer equations (4.19), (4.22), and (4.23) with the initial conditions assumed to be zero. All estimated damper currents

match the simulated damper currents and are equal to zero to five decimal places, as expected from a synchronous generator that operates in steady state.

The error between the estimated and simulated currents can be calculated using the formula,

$$\%error = \frac{\left\| i_{simulated} - i_{observed} \right\|_2}{\left\| i_{simulated} \right\|_2} \times 100 \, , \tag{4.24}$$

where $\left\| \; \right\|_2$ denotes the 2-norm (square root of the sum of the squares of all the elements). A discussion of norms is offered in Chapter 5. The errors in the three damper winding currents i_D, i_G, and i_Q for the steady state data case are 0.16%, 0.28% and 0.14% respectively.

In the second simulated case study (E-NF-00-02), transient data were considered. A permanent line to line fault was applied at 0.25 seconds between phases b and c. The observed damper currents as compared to the EMTP simulated damper currents for each axis can be seen in Figs 4.6, 4.7, and 4.8. As can be seen from the graphs, the estimated damper currents match the simulated damper currents. The percent errors between the simulated and estimated damper currents can be calculated in the same way as in the steady state case. The errors in the three damper winding currents i_D, i_G, and i_Q for the transient data case are 0.03%, 0.63% and 0.16% respectively. Since the difference between the simulated and estimated signals is not discernible in Figs 4.6, 4.7, and 4.8, a portion of i_Q as shown in Fig. 4.8 was magnified to visualize the difference between the two signals. This difference is shown in Fig. 4.9.
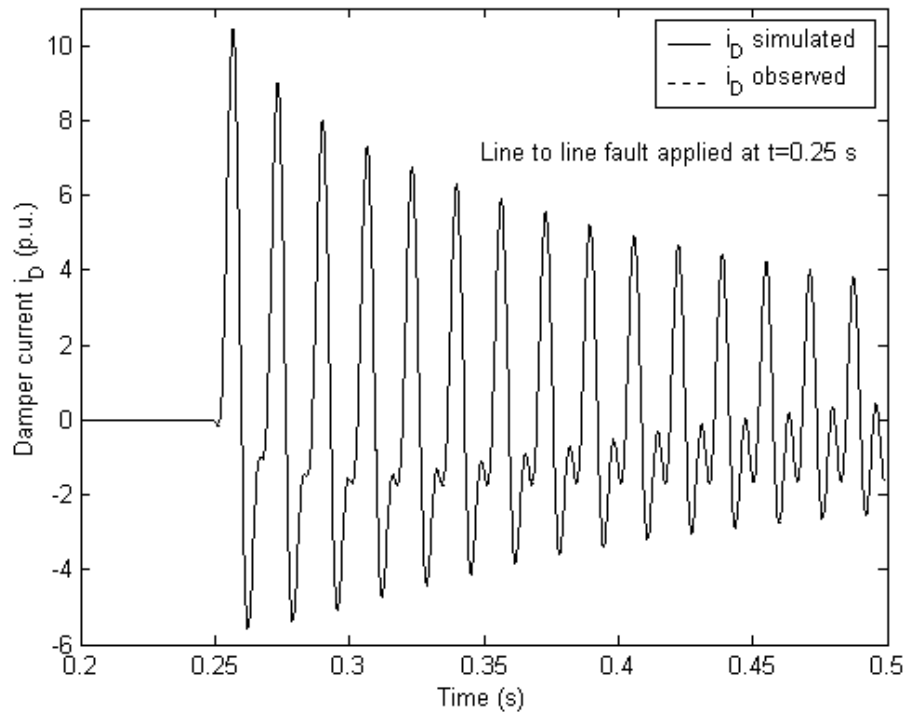
Fig. 4.6. Simulated and estimated *D*-winding damper currents using transient data
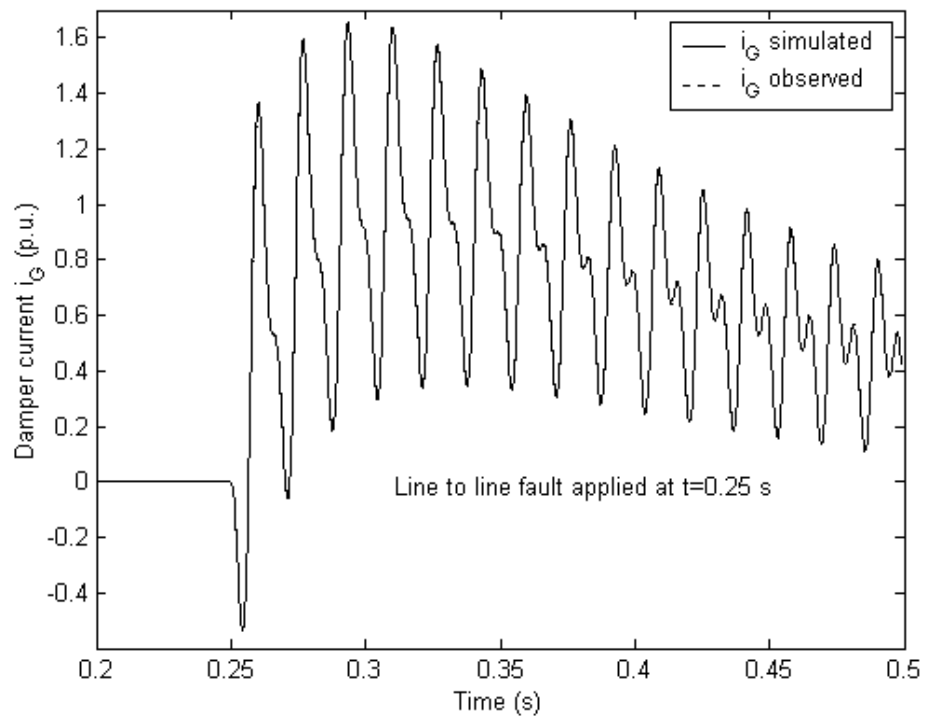
Fig. 4.7. Simulated and estimated *G*-winding damper currents using transient data
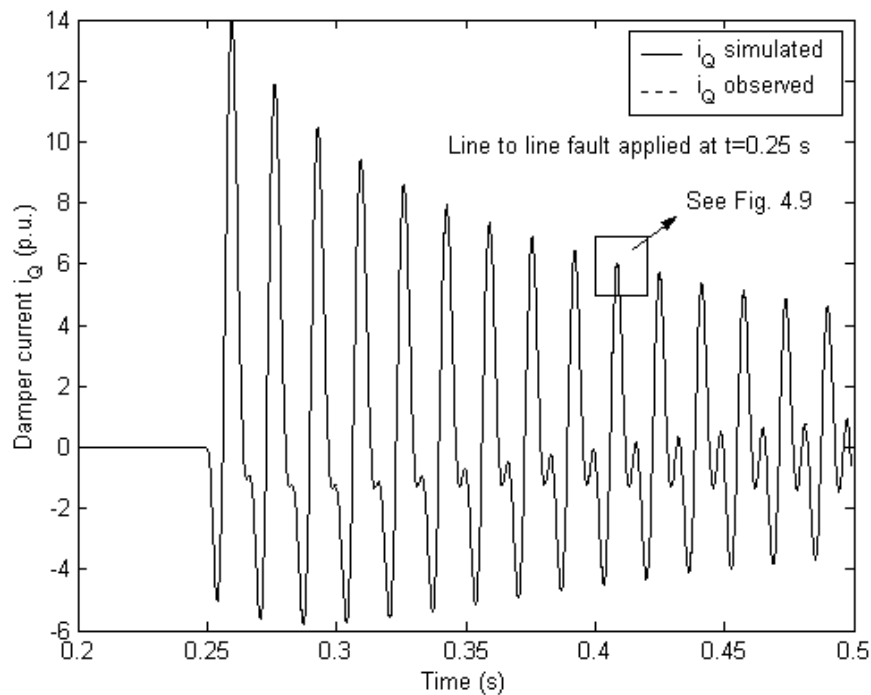
Fig. 4.8. Simulated and estimated *Q*-winding damper currents using transient data
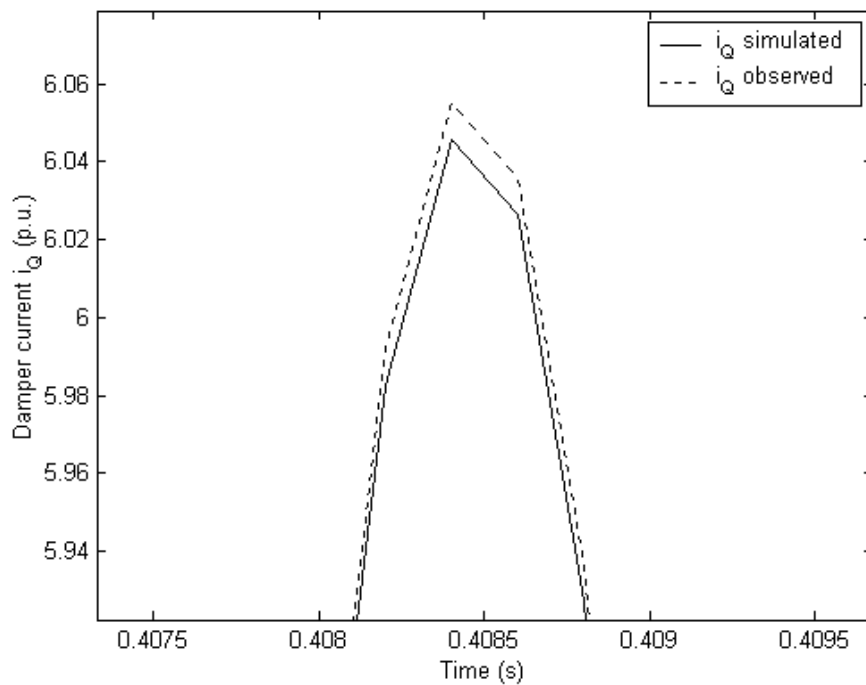
Fig. 4.9. Magnification of portion of i_Q to demonstrate the difference between the

simulated and observed signals

CHAPTER 5

STATE ESTIMATION

5.1 Introduction

State estimation is a process during which a number of unknown system state variables or parameters are assigned a value based on measurements from that system [50]. In the estimation process, any information that is known about the system is utilized. Such information may be the knowledge of the system configuration, the system constraints, the accuracy of the measuring instruments, known system parameters, previous experience from the system operation, and measurements from the system.

The system is usually arranged in the form $[H][x] = [z]$, where H is a matrix of dimensions $m \times n$, x is a vector of dimension n, and z is a vector of dimension m. In this notation m is the number of measurements and n is the number of parameters to be estimated. If $m = n$, then the system is completely determined. In other words, the number of equations is equal to the number of unknowns and if there is a solution to the system (if H is invertible), then there is a unique solution that can be found by inverting the matrix H. Therefore, $[x] = [H]^{-1}[z]$. (From hereon, the brackets denoting matrices will be dropped for simplicity, unless the context of the equation is not clear). In the overdetermined case, it is not possible to invert H since $m \neq n$. The solution is not unique since in general it is not possible to satisfy all the equations exactly for any choice of the unknowns. A solution should be selected such that the error in satisfying each equation is minimum. This error is called the residual of the solution and can be computed by,

$$r = z - H\hat{x},$$

(5.1)

where $\hat{x}$ is the vector of the estimated parameters. The residual measures how well the estimated vector $\hat{x}$ satisfies the linear system $Hx = z$. If the residual vector is zero, then $\hat{x}$ is the exact solution. However, in real systems the residual r is never zero, since the model is just an approximation of the system (linear approximation and simplifying assumptions to create a manageable model). Moreover, noise is present in the measurements because of the instrumentation and round off errors in the data recording devices. Therefore it is desired that all the entries of the residual vector be "small" in order to gain confidence in the estimated parameters. The residual vector is often an m vector, where m is usually in the range of thousands. Therefore, it is not convenient to examine the whole residual vector to ascertain the validity of the estimates. It is necessary to have a quantifying means of assigning a number to each residual vector based on its length. Such a means of measuring the size of a vector is offered by a norm.

5.2 Theory of norms

A vector norm is a function that assigns a nonnegative real number $\|x\|$ to each vector $x \in \mathfrak{R}^n$. There are a number of functions that can calculate a norm and the selection of a certain function is based on the application and on the ease of computation of the specified norm. Nevertheless, all norms satisfy the following properties,

$$
\begin{aligned}
&\|x\| \geq 0 \\
&\|x\| = 0 \Leftrightarrow x = 0 \\
&\|\alpha x\| = |\alpha| \|x\| \\
&\|x + y\| \leq \|x\| + \|y\|,
\end{aligned}
\tag{5.2}
$$

for all $x, y \in \Re^n$ and all constants α [106], [107]. The first two properties force all vectors but the zero vector to have positive length. The third property states that $-x$ and x have the same length and that $2x$ has twice the length of x. Finally, the last property is the triangle inequality which states that the sum of the sides of a triangle is never smaller than the length of the third side.

In general, the Hölder definition of a vector norm is defined by,

$$\|x\|_p = \left(|x_1|^P + |x_2|^P + \cdots + |x_n|^P\right)^{1/p},$$ (5.3)

where x_i are the elements of vector x and p is any number such that $p \geq 1$. One can compute the norm of a vector using any value of p (even non-integer). In practice, three p-norms are used: the 1-norm (or L_1), the 2-norm (or L_2), and the infinity-norm (or L_∞). The selection of these norms is based on their ease of computation and their applicability in various problems. In the solution of an overdetermined system of equations of the form $Hx = z$, the objective is to minimize the pth norm of the vector of the residuals,

$$\min \|r\|_p = \|H\hat{x} - z\|_p,$$ (5.4)

using any value for p.

The L_1 norm also known as the grid norm or the norm of the least sum of the absolute deviations is given by,

$$\|x\|_1 = |x_1| + |x_2| + \cdots + |x_n| = \sum_{i=1}^{n} |x_i|.$$ (5.5)

The minimization of the Hölder 1-norm effectively minimizes the sum of the absolute deviations and therefore it is possible to downplay the effect of outliers (inconsistent

observations with the remainder of the measurements). For this reason, the 1-norm is considered as a robust norm. A robust estimation will produce estimates which are consistent with different data sets containing noise that is not correlated between data sets.

The L_2 norm also known as the least squares or Euclidean norm is given by,

$$\|x\|_2 = (|x_1|^2 + |x_2|^2 + \cdots + |x_n|^2)^{1/2} = (x^T x)^{1/2},$$

(5.6)

and is traditionally the most widely used norm because it can be easily implemented as can be seen in Section 5.4. Minimization of the residual vector in a least squares sense in effect solves the system so that the sum of the squares of the error of each equation is minimized. The method of least squares gives the best linear unbiased estimate for any distribution with finite variance [108].

The L_∞ norm also known as the maximum or Chebyshev norm is given by,

$$\|x\|_\infty = \max_{1 \le i \le n} |x_i|,$$

(5.7)

and minimizes the largest residual. This norm is useful in applications where there is a prescribed maximum limit for any given residual. Whereas both the L_1 and L_2 norms permit isolated large residuals, in the case of experimental data L_∞ is not a robust norm since it assigns high weight on large residuals that do not have an influence on the computed solution [109].

In order to visualize the major norms that are usually used, the loci that occur from the calculation of each of the 1, 2, and infinite unit norms for a three dimensional vector are displayed in Fig. 5.1. The 1-norm results in an octahedron, the 2-norm in a

sphere, and the infinity-norm in a cube. In general the three norms obey the inequality [106],

$$\|x\|_1 \geq \|x\|_2 \geq \|x\|_\infty \quad \forall x \in \Re^n . \tag{5.8}$$

L_1 L_2 L_∞
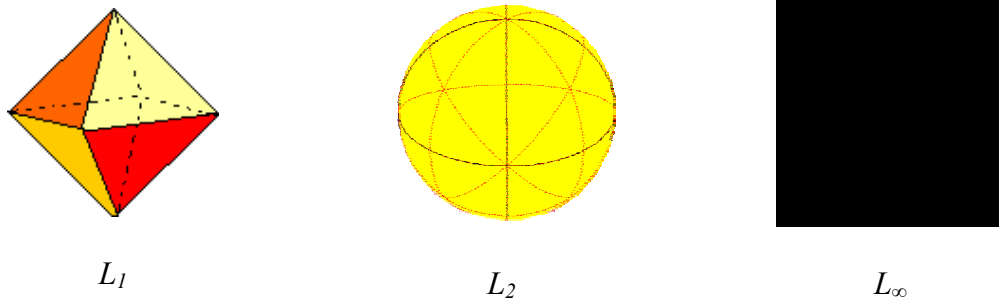
Fig. 5.1. Loci of the three major unit Hölder norms for a vector $x \in \Re^3$

5.3 Selection of the minimization norm

The selection of the minimization norm is often critical in a variety of applications. The L_∞ method has been traditionally used extensively in astronomy for the determination of the orbits of planets by philosophers such as Laplace [110] and Legendre [111]. Legendre was also the first one to propose the least squares method to solve a system of inconsistent, overdetermined equations [111]. According to the original explanation by Legendre, "By this method, a kind of equilibrium is established among the errors which, since it prevents the extremes from dominating, is appropriate for revealing the state of the system which most nearly approaches the truth." The L_2 norm has been traditionally adopted a few years later by most applications in science and later in engineering because of its ease of computation and the fact that it is easy to

comprehend and relate to real life examples. An estimator based on the L_2 minimization method is easy to be implemented by means of matrix algebra. Moreover, for a Gaussian error distribution, the L_2 method is optimal. On the other hand, the L_1 norm was shown to be extremely robust and has been used extensively in applications such as robust estimation, model fitting (constrained and unconstrained), analysis of variance, and hypotheses testing.

It is therefore necessary to test all possible norms and deduce which ones are applicable for the problem under consideration. Since p norms other than 1, 2, and ∞ lead to cumbersome calculations and have no definite benefits on the estimation results, these are rejected in advance. Two important objectives of the estimation method in this research work are to propose an estimator that is both simple in concept and fast in implementation. Use of minimization norms other than 1, 2, and ∞ defeat both objectives.

For the purposes of the synchronous generator parameter estimation, a study was conducted to compare the results of the three major norms in minimizing the residual [77]. In this study, the three solutions were evaluated based on the accuracy of the results and on the computation time required by each method. The methodology behind the estimation procedure will be deferred to subsequent sections since it is the same as the methodology adopted for this research work. This section and Section 5.4 will concentrate on the results obtained by the minimization of the residual based on the three candidate norms.

For illustration purposes it is desired to estimate three parameters, namely the stator phase resistance r, the equivalent field winding resistance r_F, and the equivalent quadrature axis inductance L_q. The measurements were generated by the numerical solution of the differential equations that describe the model as developed in Section 2.5. In this case however, the model comprises five equations and not seven as in (2.22). This is because only one damper winding was considered. Since the measurements are synthetic, the values of all parameters are known exactly and a definite comparison can be performed for the error of the estimation for each minimization method. Two sets of measurements are used for the purposes of this example, resulting in a system of ten equations and three unknowns.

Two case studies were performed. In the first case study (denominated as case S-NF-03-03), a small amount of noise was added to the measurements. This noise was added to only one of the voltage measurements and the signal-to-noise ratio (SNR) is in the order of 7000. Essentially, the measurement sets are noise free. In the second case study (S-NC-03-04), a more significant amount of noise is added. The SNR is in the order of 50, and the noise is added primarily to the voltage measurements. The purpose of the two studies is to compare the performance of all three methods under both noise free and noise contaminated conditions. For both cases, the example eventually reduces into a matrix equation of the form,

$$Hx = z , \qquad\qquad (5.9)$$

where H is a 10x3 coefficient matrix, x is a 3x1 vector of the unknown parameters, and z is a 10x1 vector of measurements.

A brief description of each method is in order. For the $p = 1$ case, it is desired to minimize the sum of the absolute deviations of all ten equations. Let the deviation for each equation be denoted by r_i. Since r_i is either positive, negative, or zero, it can be declared that,

$$r_i = r_i^+ - r_i^-,$$
(5.10)

where $r_i^+ \geq 0$, $-r_i^- \geq 0$, and $r_i^+ \times r_i^- = 0$ [112]. The problem is solved using linear programming. After adding the artificial variables A_i for each equation, the problem becomes,

$$\min \sum_{i=1}^{10} (r_i^+ + r_i^-) + M \sum_{i=1}^{10} A_i,$$
(5.11)

subject to,

$$[I, -I, H, -H] \begin{bmatrix} r^+ \\ r^- \\ x^+ \\ x^- \end{bmatrix} = z.$$
(5.12)

This formulation is readily solved by setting up a tableau according to the simplex method [112]. There are ten initial basis variables (the artificial variables A_i), and 26 state variables in the objective function.

For the $p = 2$ case, it is desired to minimize the sum of the squares of the deviations of each row in the matrix equation. Such a minimization is achieved by obtaining the pseudoinverse of matrix H,

$$\hat{x} = H^+ z,$$
(5.13)

where one form of the pseudoinverse may be given by,

$$H^+ = (H^T H)^{-1} H^T.$$ (5.14)

The pseudoinverse will be revisited and analyzed in the next section.

For the $p = \infty$ case, it is desired to minimize the maximum of the absolute deviations r_i. Let the objective function be denoted by s. Therefore,

$$\min s = \max_i |r_i| = \|Ax - b\|_\infty,$$ (5.15)

subject to,

$$\begin{bmatrix} H & e \\ -H & e \end{bmatrix} \begin{bmatrix} x \\ s \end{bmatrix} \geq \begin{bmatrix} z \\ -z \end{bmatrix},$$ (5.16)

where e is a vector of ones, with the number of rows being equal to the number of rows of H. Since the constraints are inequality constraints, it is necessary to add both a surplus and an artificial variable to each equation, in order to solve this problem as a linear programming problem. Therefore, the linear programming problem becomes,

$$\min \left[s + M \sum_{i=1}^{20} A_i \right],$$ (5.17)

subject to,

$$\begin{bmatrix} H & e \\ -H & e \end{bmatrix} \begin{bmatrix} x \\ s \end{bmatrix} - [X] + [A] = \begin{bmatrix} z \\ -z \end{bmatrix},$$ (5.18)

where X and A are vectors that incorporate the surplus and artificial variables respectively. The initial basis variables in the tableau incorporate the artificial variables A_i, while for this example, the total number of variables in the objective function is 44.

5.4 Analysis of case studies

The parameter estimation method for the three norms as analyzed in the previous section is applied to a sample synchronous generator whose parameters are known exactly. The values of the three parameters that are desired to be estimated are as shown in Table 5.1. As mentioned in Section 5.3, it is desired to perform two case studies to study the effect of noise in the parameter estimation using the three norms. In the first case study (S-NF-03-03), a small amount of noise was added to the measurements to slightly perturb the solution of the system (the measurements are synthetic, and therefore the error in the estimated parameters would have been zero). This noise was added to only one of the voltage measurements and the signal-to-noise ratio (SNR) was in the order of 7000. Essentially, the measurement sets were noise free. In the second case study (S-NC-03-04), a more significant amount of noise was added. The SNR was in the order of 50, and the noise was added primarily to the voltage measurements. Fig. 5.2 shows a flowchart of the procedure followed to obtain the results for the example under consideration.

The results for all three cases for both low noise data and high noise data are depicted in Tables 5.2 and 5.4 respectively. The residuals for $p = 1$, 2, and ∞ are computed for each set of estimated parameters and are also depicted in Tables 5.2 and 5.4. It is noted that as expected, the residuals on the diagonal are less than or equal to the other residuals in their columns. For example, for the $p = 2$ case, it is expected that the least squares residual is smaller than or equal to the least squares residuals of the $p = 1$ and $p = \infty$ cases.

Tables 5.3 and 5.5 show the percent errors of the estimated parameters relative to the exact values of those parameters. An "average" error for each case is also computed to give a better idea of the accuracy of the estimation for each case.
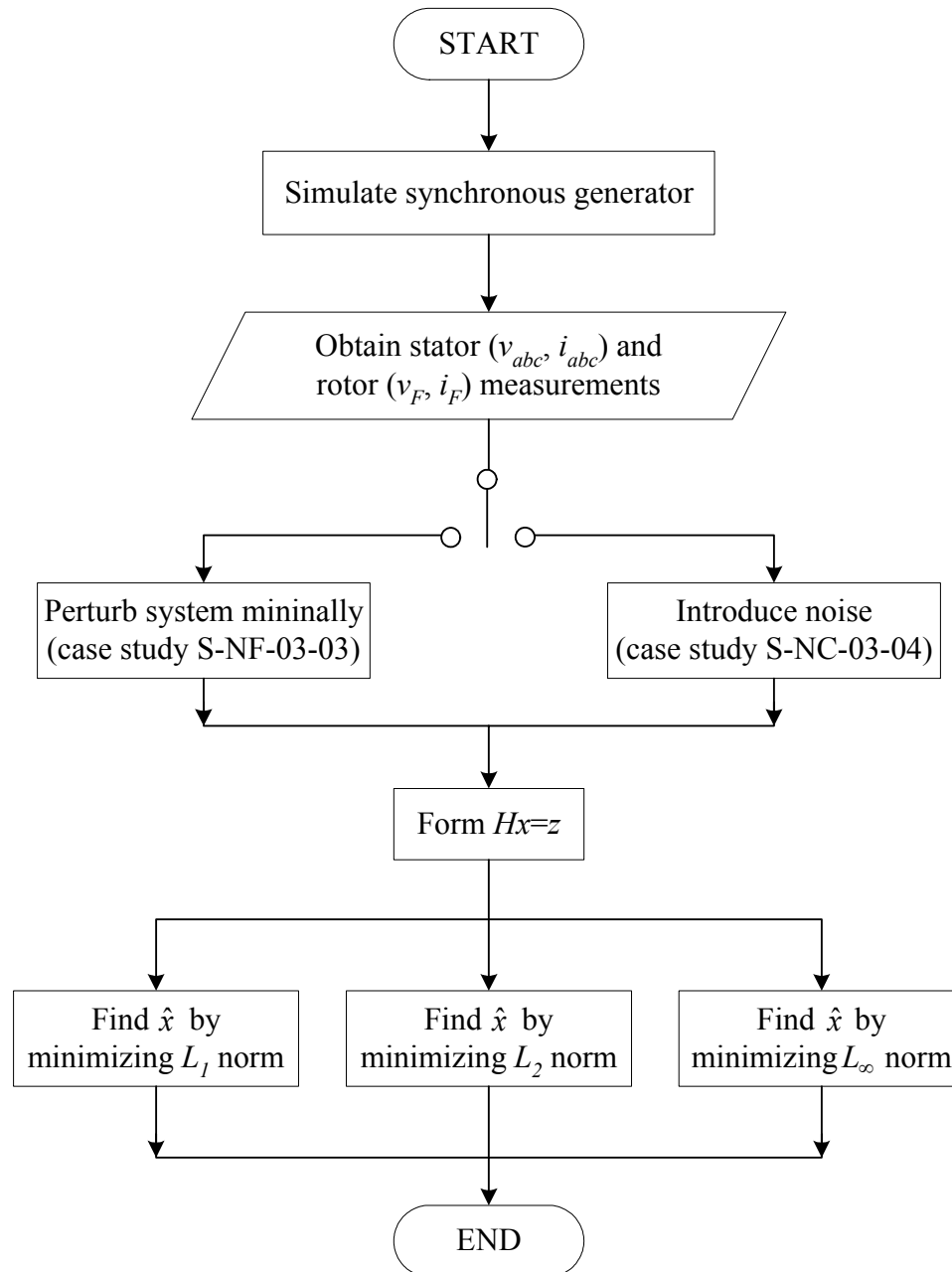
Fig. 5.2. Flowchart for example on norm minimization selection

TABLE 5.1

Exact values of synchronous generator parameters

r (p.u.)	r_F (p.u.)	L_q (p.u.)
4.6×10^{-3}	9.722×10^{-4}	1.72

TABLE 5.2

Estimated generator parameters and residuals for case study S-NF-03-03 (low noise)

	r (p.u.)	r_F (p.u.)	L_q (p.u.)	R_1	R_2	R_∞
$p = 1$	4.566857×10^{-3}	9.73697×10^{-4}	1.719874	2×10^{-4}	2×10^{-4}	2×10^{-4}
$p = 2$	4.566857×10^{-3}	9.73697×10^{-4}	1.719988	2×10^{-4}	1.41×10^{-4}	1×10^{-4}
$p = \infty$	4.566857×10^{-3}	9.73697×10^{-4}	1.719988	2×10^{-4}	1.41×10^{-4}	1×10^{-4}

TABLE 5.3

Percent errors of estimated generator parameters for case study S-NF-03-03 (low noise)

	r (p.u.)	r_F (p.u.)	L_q (p.u.)	"average error"
$p = 1$	-0.72	0.154	-0.00735	0.2938
$p = 2$	-0.72	0.154	-0.00071	0.2916
$p = \infty$	-0.72	0.154	-0.00071	0.2916

TABLE 5.4

Estimated generator parameters and residuals for case study S-NC-03-04 (high noise)

	r (p.u.)	r_F (p.u.)	L_q (p.u.)	R_1	R_2	R_∞
$p = 1$	5.4811×10^{-3}	-228.26×10^{-4}	1.6712	0.2948	0.1369	0.091
$p = 2$	7.7669×10^{-3}	9.1284×10^{-4}	1.7277	0.2948	0.1103	0.059
$p = \infty$	-57.38×10^{-3}	0	1.5753	0.4048	0.1380	0.059

TABLE 5.5

Percent errors of estimated generator parameters for case study S-NC-03-04 (high noise)

	r (p.u.)	r_F (p.u.)	L_q (p.u.)	"average error"
$p = 1$	19.16	-2448	-2.84	823.3
$p = 2$	68.85	-6.11	0.45	25.14
$p = \infty$	-1347	100	-8.41	485.1

In the low noise case, it is observed that the solutions to the problem are almost identical when using any of the norms under study. Nevertheless, $p = 2$ and $p = \infty$ give greater accuracy of estimation in one parameter, and a smaller residual, thus causing them to be the favored solutions. The comparison is mainly based on the percent errors of each parameter and not on the resulting residual, since as shown before, it is always true that,

$$\|x\|_1 \geq \|x\|_2 \geq \|x\|_\infty \quad \forall x \in \Re^n . \tag{5.19}$$

In the high noise case the L_2 norm is clearly the best minimization norm for this particular example. The percent errors in the estimation of some of the parameters in the $p = 1$ and $p = \infty$ cases are unacceptable, and therefore it seems that these cases are particularly sensitive for these noisy data. On the other hand, the method of least squares seems to be able to reduce the effect of the excessive noise in the measurements. Another important consideration in the selection of the minimization method is the computation time. Since this problem consists of only ten equations, the computation time for all three cases is negligible and therefore, no computational burden will be

imposed no matter which norm is selected. However, for larger problems, in general $p = 2$ is the fastest minimization method.

As far as ease of computation is concerned, the L_2 minimization method is by far the most easy to implement because of the availability of clearly defined and well tested computer algorithms such as the pseudoinverse which will be analyzed in the next section. The implementation of the L_1 and L_∞ minimization methods require the use of linear programming which may become quite complicated for large systems. Another possible method to implement the L_1 and L_∞ solution of a system is via the use of the iteratively reweighted least squares method (IRLS). Nevertheless, the IRLS method requires a certain number of iterations, which render this approach slow to implement.

As noted in the previous section, a possible advantage of the L_1 minimization method is its robustness with respect to outlier rejection. However, if adequate prefiltering mechanisms and bad data detection and rejection algorithms are utilized, then this powerful advantage of the L_1 method will be negated, again making the L_2 method more efficient and accurate.

The above example and related arguments indicate that the minimization method that should be selected for this work is the least squares method based on the L_2 norm. An analysis of the least squares technique and its implementation for the synchronous generator parameter estimation algorithm is presented in the following sections.

5.5 Least squares and the Moore-Penrose pseudoinverse

As described in Chapter 2, the resulting model can be rearranged in the form,

$$Hx = z,$$

$$(5.20)$$

where H is a matrix of dimensions $m \times n$ containing the coefficients of the unknown parameters, x is a vector of dimension n that is desired to be estimated, and z is a vector of dimension m containing measurements obtained from the system. Since $m > n$, (5.20) constitutes an overdetermined system of equations that usually does not have an exact solution. Therefore, it is desired to find a solution vector $\hat{x}$ that minimizes the quantity,

$$f(\hat{x}) = (z - H\hat{x})^T (z - H\hat{x}) = \|z - H\hat{x}\|_2^2.$$

$$(5.21)$$

The right hand side of (5.21) is equal to the square of the 2-norm of the residual vector. By (5.6) the problem can be reformulated as the desire to find a solution such that the sum of the squares of the residual of each equation is minimal, thus the name least squares solution is given to the solution vector $\hat{x}$.

Using (5.21), it is desired to find a convenient form of representing $\hat{x}$ in terms of the known matrix-vector pair H, z. The minimum of a function occurs at the point where its derivative is equal to zero. Differentiating (5.21) with respect to $\hat{x}$,

$$\frac{\partial f}{\partial \hat{x}} = \begin{bmatrix} \dfrac{\partial f}{\partial \hat{x}_1} \\ \dfrac{\partial f}{\partial \hat{x}_2} \\ \vdots \end{bmatrix} = \frac{\partial}{\partial \hat{x}} [z^T z - \hat{x}^T H^T z - z^T H\hat{x} + \hat{x}^T H^T H\hat{x}] = 0$$

$$\Rightarrow 0 - 2H^T z + 2H^T H\hat{x} = 0$$

$$\Rightarrow H^T H\hat{x} = H^T z.$$

$$(5.22)$$

Hence, if $\left[H^T H\right]^{-1}$ exists the vector of the estimated parameters can be found by,

$$\hat{x} = \left[H^T H\right]^{-1} H^T z.$$ (5.23)

The quantity $\left[H^T H\right]^{-1} H^T$ is termed as the Moore-Penrose pseudoinverse or the generalized inverse and is symbolized by H^+. The pseudoinverse also exists if $\left[H^T H\right]$ is not invertible. If $\left[HH^T\right]^{-1}$ exists, then the pseudoinverse is given by $H^T \left[HH^T\right]^{-1}$. If none of the above inverses exist, then the pseudoinverse can be found by the method of the singular value decomposition [106]. The pseudoinverse is unique. It should be noted that in the case of a square matrix $H^+ = H^{-1}$. The mathematical definition of the pseudoinverse (or of any other generalized inverse) is accompanied by four conditions known as the Penrose conditions [43]. H^+ is defined as the pseudoinverse of H if and only if these four conditions are satisfied:

$$1.\ HH^+ H = H$$
$$2.\ H^+ HH^+ = H^+$$
$$3.\ (HH^+)^T = HH^+$$
$$4.\ (H^+ H)^T = H^+ H.$$ (5.24)

The solution to the system (5.20) can be calculated using a variety of techniques including the Cholesky factorization [106], the QR factorization [106], [113], and the singular value decomposition (SVD) [106], [113]. The technique chosen in the implementation of the estimator is the SVD since it is the most accurate. Its computational time is greater than the other available methods but the accuracy of the method is the prevailing factor for its use. The SVD is directly related to the calculation

of the pseudoinverse as developed above and it is a proven stable method for the solution of least squares problems.

5.6 Configuration of the state estimator

As shown in Sections 2.5 and 5.4 it is desired to arrange the equation of the model (3.11) in the form $Hx = z$. The developed model of the synchronous machine is of the form,

$$V = -RI - LI',$$
(5.25)

where V, I, and I' are vectors of the system voltages and currents, and R and L are matrices containing the system constant parameters. As explained in Chapter 4, some of the current states are not possible to be measured, but they are possible to be estimated. Therefore the voltage and current vectors are known. Moreover, some of the elements of matrices R and L are also known, whereas the rest of the elements need to be estimated. An important drawback is that the current derivative vector I' is not known. Therefore, it has to be assigned values through an approximation.

Numerical differentiation of measured signals can create numerous problems in practice, since the division by the small time step between the measurements leads to the amplification of high frequency noise. Usually, in most applications only a single differentiation is possible even if a proper noise filter is implemented. For this reason, the selection of the differentiation formula to approximate the derivative needs to be carefully selected. Appendix D considers a least squares estimation of the coefficients of a differential equation using five methods for the calculation of the derivatives of the

signal. Three of the proposed methods use formulae obtained from the approximation of derivatives via the use of the interpolation polynomial, whereas two methods use integration formulae modified so as to accommodate the estimation problem at hand.

Various case studies were performed with both varying time step between the measurements and noise free/noise contaminated measurements. Although, when no noise was present Simpson's rule and higher order differentiation formulae prevailed in the accuracy of the estimated parameters, when noise was added to the measurements, the first order differentiation formula (forward difference formula),

$$i'(t) \approx \frac{i(t + \Delta t) - i(t)}{\Delta t},$$
(5.26)

was clearly the best choice for the approximation of the derivatives of the signal and for the estimation of the unknown parameters.

Once all the data are obtained and the numerical differentiation is performed, the matrix equation needs to be rearranged in the form $Hx = z$, where H and z are a known matrix and vector respectively. At the same time, it is desired that an algorithm be found such that it will be possible to select which parameters are to be estimated with no need to rearrange the code of the program. In such a way, the algorithm can be easily adapted by a visual platform since this is one of the major objectives of this research work.

To show how this algorithm works and how the data are arranged in the desired form, (3.11) is reconsidered. Since the last three equations of the synchronous generator model have been used for the development of the observer, the remaining four equations will be used for the implementation of the estimator. Assuming that parameters L_{AD}, L_{AQ},

and r_F are desired to be estimated, and rearranging the equation in the form $Hx = z$, the following matrix equation is obtained.

$$
\begin{bmatrix}
0 & 0 & 0 \\
\frac{1}{\omega_B}(i'_d + i'_F + i'_D) & \omega(i_q + i_G + i_Q) & 0 \\
-\omega(i_d + i_F + i_D) & \frac{1}{\omega_B}(i'_q + i'_G + i'_Q) & 0 \\
\frac{1}{\omega_B}(i'_d + i'_F + i'_D) & 0 & i_F
\end{bmatrix}
\begin{bmatrix} L_{AD} \\ L_{AQ} \\ r_F \end{bmatrix}
= -
\begin{bmatrix}
r + 3r_n & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & r & \omega\ell_q & 0 & 0 & 0 & 0 \\
0 & -\omega\ell_d & r & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix} i_0 \\ i_d \\ i_q \\ i_F \\ i_D \\ i_G \\ i_Q \end{bmatrix}
$$

$$
- \frac{1}{\omega_B}
\begin{bmatrix}
L_0 + 3L_n & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \ell_d & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \ell_q & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \ell_F & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix} i'_0 \\ i'_d \\ i'_q \\ i'_F \\ i'_D \\ i'_G \\ i'_Q \end{bmatrix}
-
\begin{bmatrix} V_0 \\ V_d \\ V_q \\ -V_F \\ -V_D \\ -V_G \\ -V_Q \end{bmatrix}. \qquad (5.27)
$$

In this way, the four unknown parameters and their coefficients are isolated on the left hand side, and all elements of the right hand side are known. Moreover, the right hand side reduces to a vector and therefore the system takes the final form $Hx = z$. It should be noted that (5.27) is constructed using data from a single time step. The resulting system will consist of a large number of equations identical to (5.27) to reflect every time step in the available measurements. For example, if m measurements (data points) are obtained, then this system will have $4m$ equations.

5.7 Summary

This chapter concentrated on the theory supporting state estimators, norm selection and minimization, and the configuration of a state estimator for parameter identification. Table 5.6 summarizes some useful definitions for vector norms and some

common properties.   Table 5.7 depicts some of the concepts pertaining to the

pseudoinverse of a matrix, while Fig. 5.3 shows a pictorial of the estimator for the

parameter identification of a synchronous generator.

TABLE 5.6

Definitions and properties of vector norms

Definitions and properties	Description
$\|x\| \geq 0$ $\|x\| = 0 \Leftrightarrow x = 0$ $\|\alpha x\| = |\alpha| \|x\|$ $\|x + y\| \leq \|x\| + \|y\|$,	All norms satisfy these properties
$\|x\|_p = (|x_1|^p + |x_2|^p + \cdots + |x_n|^p)^{1/p}$	Definition of a p norm ($p \geq 1,\ p \in \Re$)
$\|x\|_1 = |x_1| + |x_2| + \cdots + |x_n| = \sum_{i=1}^{n} |x_i|$	1-norm, or grid norm
$\|x\|_2 = (|x_1|^2 + |x_2|^2 + \cdots + |x_n|^2)^{1/2} = (x^T x)^{1/2}$	2-norm, or least squares norm
$\|x\|_\infty = \max_{1 \leq i \leq n} |x_i|$	∞-norm, or maximum norm
$\|x\|_1 \geq \|x\|_2 \geq \|x\|_\infty \quad \forall x \in \Re^n$	Relationship between 1,2, and ∞ norms

TABLE 5.7

Concepts pertaining to the pseudoinverse of a matrix

Equation	Description
$\hat{x} = H^+ z$	Solution of an overdetermined linear system
$H^+ = (H^T H)^{-1} H^T$	One of the possible methods to calculate the pseudoinverse of a matrix
$f(\hat{x}) = (z - H\hat{x})^T (z - H\hat{x}) = \|z - H\hat{x}\|_2^2$	The least squares solution is equivalent to the minimization of this function – relationship to the 2-norm
1. $HH^+ H = H$ 2. $H^+ HH^+ = H^+$ 3. $(HH^+)^T = HH^+$ 4. $(H^+ H)^T = H^+ H$.	Any pseudoinverse should satisfy these requirements
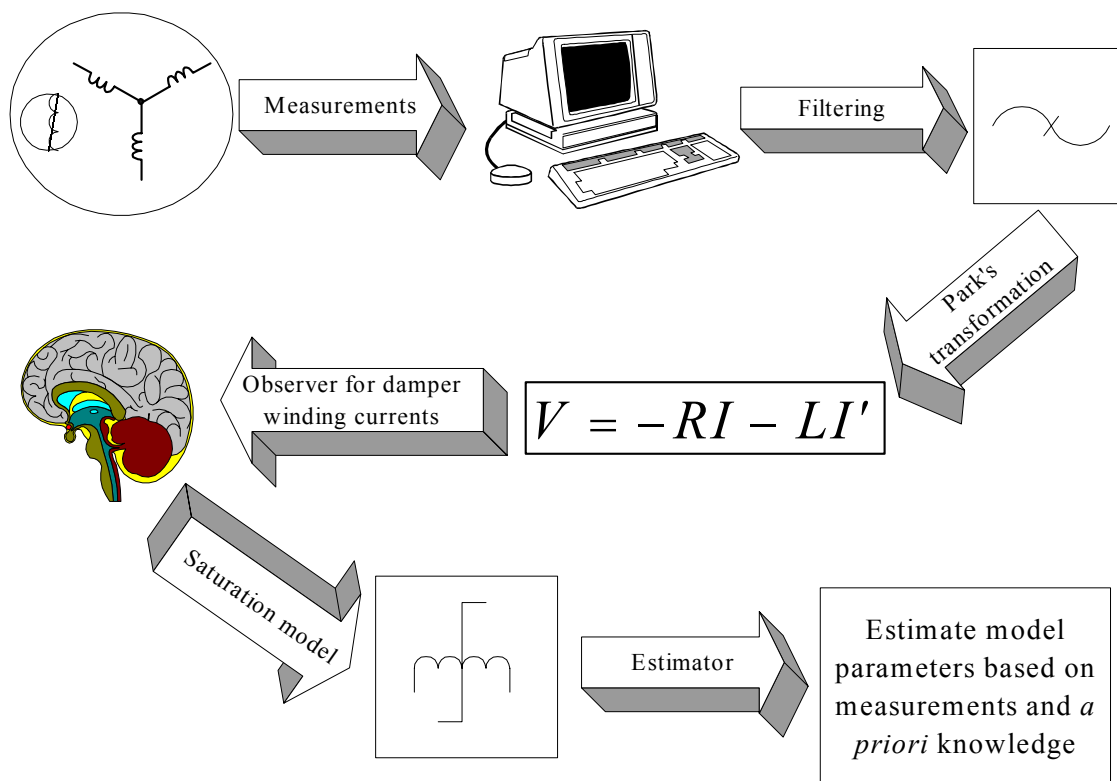
Fig. 5.3. Pictorial of an estimator for synchronous generator parameter identification

CHAPTER 6

PARAMETER ESTIMATION USING SYNTHETIC DATA

6.1 Introduction

The work performed in Chapters 2, 3, and 5 enabled the development of the synchronous generator model that is used in this research work and the configuration of the state estimator in order to implement the parameter identification procedure. To ascertain the correctness and the validity of the algorithm to be developed, it is of vital importance to test it with data for which the parameters to be estimated are known. In this way, the algorithm can be tested for conceptual or unintended errors, and the accuracy of the method can be evaluated.

The testing of the algorithm needs to be performed in three stages. First, the algorithm needs to be tested with synthetic noise free data generated by the direct numerical solution of the differential equations of the model as depicted in (3.11). This stage will illustrate whether the system is stable under various disturbances and whether the estimation is possible to be performed. Ideally, the deviations of the estimates from their true value should be very small, and in effect comparable to the round off error of the computer that is used to perform the estimation. This procedure does not produce any distinguishing results for the candidate models since, as expected, all parameters are estimated exactly. Nevertheless, this procedure is an important part of the algorithm development procedure as it offers reassurance in the estimation process and in the viability of the algorithm. The results for the estimation of the parameters using this method will not be presented in this dissertation. An explanation of the procedure and some preliminary results are offered in [114].

The second stage of the algorithm testing is to implement the estimation process with synchronous generator data that are noise free. Since all measurements from synchronous generators contain a finite unknown amount of noise, it is useful to first simulate the synchronous generator using a program that is currently used by utilities such as the Electromagnetic Transients Program (EMTP). EMTP is suitable for testing the estimation algorithm because data from the simulation are free of noise, and one has access to all generator parameters and signals. Consequently, "measurements" of the system can be obtained, and a good assessment of the viability of the designed estimator can thus be performed. Parameter estimation with EMTP noise free data will be the subject of this chapter.

Finally, the estimator needs to be tested using actual generator data. Firstly, generator data obtained from the same generator that has been simulated in the second stage of the testing of the algorithm are used to obtain solid conclusions about the estimation method. If the results of the estimation with data from such a generator are satisfactory, data sets from other generators should be used for a final evaluation of the algorithm. Parameter estimation using actual measurements is considered in Chapter 8.

6.2 Calculation of generator parameters

The parameters of the synchronous generator model as depicted in (2.22) and (3.11) need to be calculated for a specific synchronous generator. This calculation will enable the simulation of the generator to obtain "measurements" of the system, and will offer the opportunity to compare the estimated parameters with the actual parameters and

deduce whether the proposed algorithm can be implemented. Synchronous generator parameters can be calculated using a combination of sources, namely the manufacturer stability data and saturation curve for a specific generator, equivalent circuit calculations, or even from IEEE standards [5], [6] that specify data for a number of different synchronous generators for demonstration purposes.

In this case, the generator constants are calculated using the manufacturer stability data sheet and the saturation curve for the generator under study. Using data for an existing generator can create more confidence in the results when actual measurements from that generator are utilized to implement the estimation. Equivalent circuits are utilized as appropriate to obtain the values of the generator parameters.

In order to illustrate the type of calculation needed and the kind of manufacturers' data required, attention turns to a specific example. The specific example is a cross-compound generator located in the southwest U.S.A. The generator contains a high pressure unit rated at 483 MVA and a low pressure unit rated at 426 MVA. This illustrative generator shall be used throughout Chapters 6, 7, and 8. For this generator, detailed calculations can be seen in Appendix A while the manufacturer's data sheet and the saturation curve can be seen in Appendix B. Table 6.1 lists the parameters and their value as calculated in Appendix A. The only difference in the parameters of Appendix A and Table 6.1 is the value of the stator resistance r. For the purposes of synthetic data the stator resistance was assigned the value of 0.0027 p.u. The difference in stator resistance does not affect any of the subsequent analysis. The inductances in Table 6.1 represent unsaturated values and are calculated via the manufacturer data as shown in Appendix A.

TABLE 6.1

Calculated parameters for use in the testing of the estimator algorithm

(Parameters are for the generator described in Appendix A)

Parameter	Value (p.u.)	Parameter name
L_0	0.15	Equivalent zero sequence inductance
L_{AD}	1.64	d axis magnetizing mutual inductance
L_{AQ}	1.56	q axis magnetizing mutual inductance
L_d	1.80	Equivalent direct axis inductance
L_D	1.68125	Self inductance of damper winding D
L_F	1.75791	Field winding self inductance
L_G	1.978537	Self inductance of damper winding G
L_n	100	Equivalent neutral inductance
L_q	1.72	Equivalent quadrature axis inductance
L_Q	1.593	Self inductance of damper winding Q
M_D	1.339054	Stator to damper winding D mutual inductance
M_F	1.339054	Stator to field mutual inductance
M_G	1.2737	Stator to damper winding G mutual inductance
M_Q	1.2737	Stator to damper winding Q mutual inductance
M_X	1.64	Rotor mutual inductance in the d axis circuit
M_Y	1.56	Rotor mutual inductance in the q axis circuit
r	0.0027	Stator phase resistance
r_D	0.0125	Equivalent resistance of damper winding D
r_F	9.722×10^{-4}	Equivalent field resistance
r_G	0.01071	Equivalent resistance of damper winding G
r_n	100	Equivalent neutral resistance
r_Q	0.01632	Equivalent resistance of damper winding Q

6.3 Estimation of generator parameters

As mentioned in Chapter 2, the system identification procedure is an iterative process with respect to the selection of the model of the system. A number of candidate models need to be tested so as to select the one that best fits the actual response of the system. Two candidate models have been proposed in Chapter 2: model 2.1 and model 2.2 as defined in IEEE Standards [83]. Further, a modification of model 2.2 has been proposed in Chapter 3 to incorporate the effect of saturation and to simplify the estimation process. The modified model will be referred to as model 2.2x. It is desired to compare the results for all three models to the manufacturer supplied parameters for the synchronous generator under consideration. Table 6.2 shows a description of some of the distinguishing characteristics of the three models. Fig. 6.1 is a flowchart for the estimation of synchronous generator parameters from simulated noise free data.

TABLE 6.2

Distinguishing characteristics of the three candidate models

Characteristic	Model 2.1	Model 2.2	Model 2.2x
Number of damper windings in the d axis	1	1	1
Number of damper windings in the q axis	1	2	2
Number of equations in the model	6	7	7
Model parameters	$r_n, L_0, L_n, r,$ $L_d, L_q, M_F,$ $M_D, M_Q, r_F,$ $r_D, r_Q, L_F, L_D,$ L_Q, M_X	Same as model 2.1 plus $r_G, L_G,$ M_G, M_Y	Same as model 2.2 but $M_X, M_Y,$ $M_F, M_D, M_G, M_Q, L_F, L_D, L_G,$ $L_Q, L_d, L_q,$ are replaced by expressions involving $L_{AD}, L_{AQ},$ and the leakage inductances
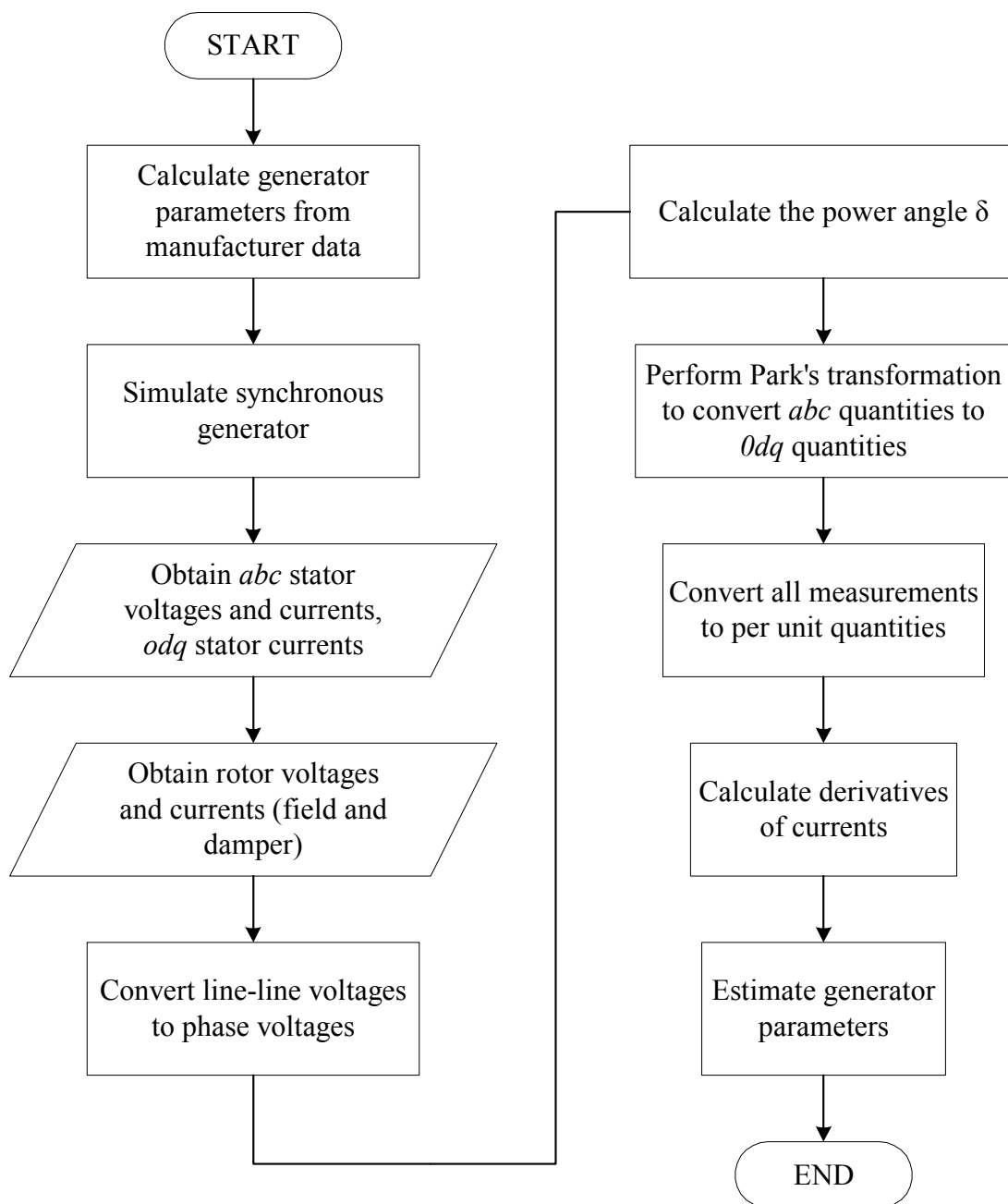
Fig. 6.1. Flowchart for synthetic data and estimator implementation

A small description of the simulated data is in order at this point. A synchronous

generator with operating parameters identical to the parameters depicted in Table 6.1 was

simulated in steady state operation in EMTP. The generator served a load with an active power demand of 356 MW and a reactive power demand of 26 MVAr. The simulation was run up to 5 s, and the sampling time for the measurements was 0.2 ms. The measurements were then read into a text file per the format described in Table E.1 of Appendix E. These measurements were then used in the parameter identification procedure as shown in the flowchart of Fig. 6.1.

Table 6.3 depicts the estimated parameters for all three models and the corresponding calculated parameters from manufacturer's data (case study E-NF-01-05). A percent error of each parameter is also depicted in the same table. All parameters have been estimated individually assuming that all other parameters are known. For all case studies saturation is considered not to have any effect on the generator inductances since the generator was simulated to run in the steady state non-saturated region. This region corresponds to the straight portion of the saturation curve as shown in Fig. B.1. Therefore, no correction for saturation needs to be performed for the estimation of any parameter in this chapter.

The results of Table 6.3 show that all parameters can be estimated accurately regardless of the model used. The maximum error obtained using models 2.1 and 2.2 is 0.39% and occurs for the field inductance L_F. The maximum error obtained using model 2.2x is 0.16% and occurs for the mutual magnetizing inductance L_{AQ}. For all three models, the stator resistance r and the field resistance r_F are estimated with 0% error.

A comparison between models 2.1 and 2.2 shows that all estimated parameters for both models are equal, so no definite conclusions can be extracted from these results as to

which model should be selected. Further, no definite comparisons can be made between model 2.2x and the other two models, since the parameters estimated with model 2.2x are different with the exception of r and r_F. Therefore, the decision as to which model is the dominant model for the parameter identification procedure will have to be relegated to the estimation using actual measurements in Chapter 8. Nevertheless, an obvious advantage of model 2.2x can be mentioned. Model 2.2x requires the estimation of less parameters and offers an easier method to implement saturation.

TABLE 6.3

Estimated parameters using EMTP generated data (case study E-NF-01-05)

Parameter	Manufacturer value (p.u.)	Model 2.1		Model 2.2		Model 2.2x	
		Estimated parameter (p.u.)	% Error	Estimated parameter (p.u.)	% Error	Estimated parameter (p.u.)	% Error
L_d	1.80	1.7986	0.08	1.7986	0.08	N/A	N/A
L_q	1.72	1.7225	0.14	1.7225	0.14	N/A	N/A
L_F	1.75791	1.7510	0.39	1.7510	0.39	N/A	N/A
kM_F	1.64	1.6408	0.05	1.6408	0.05	N/A	N/A
L_{AD}	1.64	N/A	N/A	N/A	N/A	1.6418	0.10
L_{AQ}	1.56	N/A	N/A	N/A	N/A	1.5625	0.16
r	0.0027	0.0027	0	0.0027	0	0.0027	0
r_F	$9.722x10^{-4}$	$9.722x10^{-4}$	0	$9.722x10^{-4}$	0	$9.722x10^{-4}$	0

6.4 Multiple simultaneous parameter estimation

The estimated parameters in case study E-NF-01-05 in Section 6.3 are estimated individually assuming that all other parameters are known. Although in some cases this is the desired situation in practice, in other cases it may be required to estimate more than one parameter at a time. Thus it is necessary to implement the parameter identification procedure for multiple parameter estimation to deduce whether the error characteristics of the estimation vary significantly, or even whether multiple parameter estimation is feasible. For multiple parameter estimation to be feasible it is desired that the percent error obtained for each parameter is approximately the same in both individual parameter estimation and multiple parameter estimation.

First, multiple parameter estimation for models 2.1 and 2.2 will be considered. Table 6.4 depicts the results obtained for case study E-NF-03-06. Three parameters (L_d, L_q, and r_F) were estimated simultaneously for both models. Table 6.5 shows the results obtained for case study E-NF-03-07, where L_d, L_q, and L_F were simultaneously estimated.

TABLE 6.4

Multiple simultaneous parameter estimation (case study E-NF-03-06)

Parameter	Manufacturer value (p.u.)	Model 2.1		Model 2.2	
		Estimated parameter (p.u.)	% Error	Estimated parameter (p.u.)	% Error
L_d	1.80	1.7986	0.08	1.7986	0.08
L_q	1.72	1.7225	0.14	1.7225	0.14
r_F	$9.722x10^{-4}$	$9.722x10^{-4}$	0	$9.722x10^{-4}$	0

TABLE 6.5

Multiple simultaneous parameter estimation (case study E-NF-03-07)

		Model 2.1		Model 2.2	
Parameter	Manufacturer value (p.u.)	Estimated parameter (p.u.)	% Error	Estimated parameter (p.u.)	% Error
L_d	1.80	1.7986	0.08	1.7986	0.08
L_q	1.72	1.7225	0.14	1.7225	0.14
L_F	1.75791	1.7510	0.39	1.7510	0.39

Tables 6.6 and 6.7 show two of the case studies that were performed for observing how multiple parameter estimation affects the estimated parameters in the case of model 2.2x. Table 6.6 shows the results for case study E-NF-02-08, where the magnetizing mutual inductances L_{AD} and L_{AQ} were estimated simultaneously. Table 6.7 shows the results for case study E-NF-03-09 where L_{AD}, L_{AQ}, and r_F were estimated simultaneously.

TABLE 6.6

Multiple simultaneous parameter estimation (case study E-NF-02-08)

		Model 2.2x	
Parameter	Manufacturer value (p.u.)	Estimated parameter (p.u.)	% Error
L_{AD}	1.64	1.6418	0.10
L_{AQ}	1.56	1.5625	0.16

TABLE 6.7

Multiple simultaneous parameter estimation (case study E-NF-03-09)

Parameter	Manufacturer value (p.u.)	Model 2.2x	
		Estimated parameter (p.u.)	% Error
L_{AD}	1.64	1.6418	0.10
L_{AQ}	1.56	1.5625	0.16
r_F	$9.722x10^{-4}$	$9.722x10^{-4}$	0

As seen from Tables 6.4-6.7 the estimated parameters in the multiple parameter estimation case agree with the values of the individually estimated parameters in Section 6.3. The results of all case studies clearly indicate that multiple parameter estimation is possible. Furthermore, no degradation of the estimate occurs as the number of the estimated parameters increases.

CHAPTER 7

NOISE FILTERING AND BAD DATA IDENTIFICATION

7.1 Introduction

A crucial aspect of the parameter estimation process when using actual data is the removal of outliers and inconsistent data, and the filtering of high frequency noise from the measurements. No matter how technologically advanced the measuring instruments are, or how carefully the measurements are obtained or processed, noise is always present in some form. Commonly, measurements have errors resulting mainly from meter and communication errors, incomplete metering, or inaccuracy of metering equipment. Further, round off errors (e.g. analog to digital conversion error) are usually another significant addition to inaccurate measurements. Round off errors are created by either the limited capability of the recording instrument, or by the format of the data file and the subsequent processing of the data by the computer. Therefore, prior to any estimation it is necessary to perform bad data detection and rejection, and filtering of the noise.

Another potential component of "noise" is the appearance of harmonics in several of the instrumented signals. In the field winding, $v_F(t)$ and $i_F(t)$ are usually derived from solid state controlled rectifiers and harmonics of order p, $2p$, $3p$, … (p: pulse order) appear in the "DC" field circuit. Park's transformation model does not include these harmonics nor their action on machine flux or stator signals. Similarly, in the stator, asymmetric pole configuration and pole saliency result in harmonics in the AC generated voltage. These signals are also not modeled. IEEE Standards 50.12 and 50.13 limit the harmonics by limiting the telephone influence factor (TIF). These limits are translated to about the 0.3% range for phase currents (for positive and negative sequence harmonics),

and to about 0.2% for zero sequence currents [58]. For the purposes of the parameter estimation described in this dissertation, these harmonics are neglected and assumed to be measurement noise. An observation of the magnitude of the harmonics in the signals of interest indicates that these harmonics are small and can be safely neglected without degrading the accuracy of the estimated parameters.

As mentioned in Chapter 6, eight signals are typically measured for a synchronous generator: the stator line to line voltages, the stator currents, and the rotor (field) voltage and current. The main frequency components of interest for the field measurements are at or near DC. For the stator measurements it is possible to perform filtering of the AC measurements (50-60 Hz range), or of the *0dq* transformed signals (at or near DC). Although filtering of the actual signals in the *abc* reference frame presents its own advantages, in this particular application, it was found that the stator measurements are most effectively filtered after the *0dq* transformation. This is because the *0dq* transformed signals have components of interest that are at or near DC. This is helpful in the filter design process, as the cutoff frequencies are well defined. In the case of the AC signals, depending on the generator under study, it is not known whether the 50 Hz or 60 Hz components are the fundamental components. Thus, the filter design would not be globally acceptable and would have to be redesigned based on the frequency of the power supplied by each generator. Fig. 7.1 shows the filtering and bad data detection/rejection configuration.
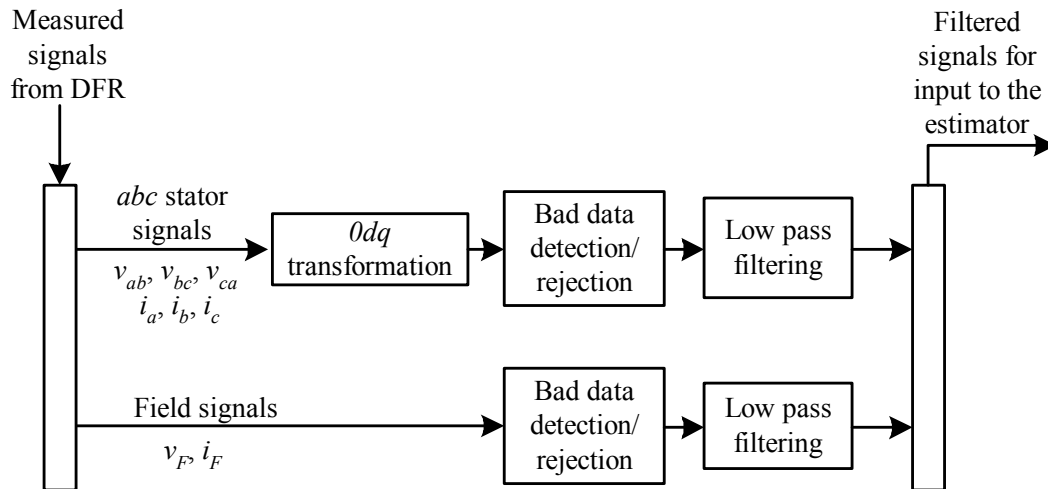
Fig. 7.1. Filtering and bad data detection/rejection configuration

7.2 Filtering

A variety of filters and filtering methods have been proposed in the literature and are implemented in all applications that require interaction with actual signals. In some cases extensive filtering is required, while in others the noise content is low and less sophisticated filters are needed. For this research work, since both types of signals that need to be filtered are DC signals, it is necessary to employ a low pass filter whose cutoff frequency is selected so as to maintain the dynamics of the signal in both steady state and transient conditions. A low pass filter ideally removes all frequency information above the cutoff frequency. In reality, a low pass filter has a response similar to that depicted in Fig. 7.2. Typically, in this application the phase response is of no interest since the signals that are desired to be filtered are DC signals. However, it is desirable that the designed filters have a flat zero phase response in the vicinity of zero Hz.
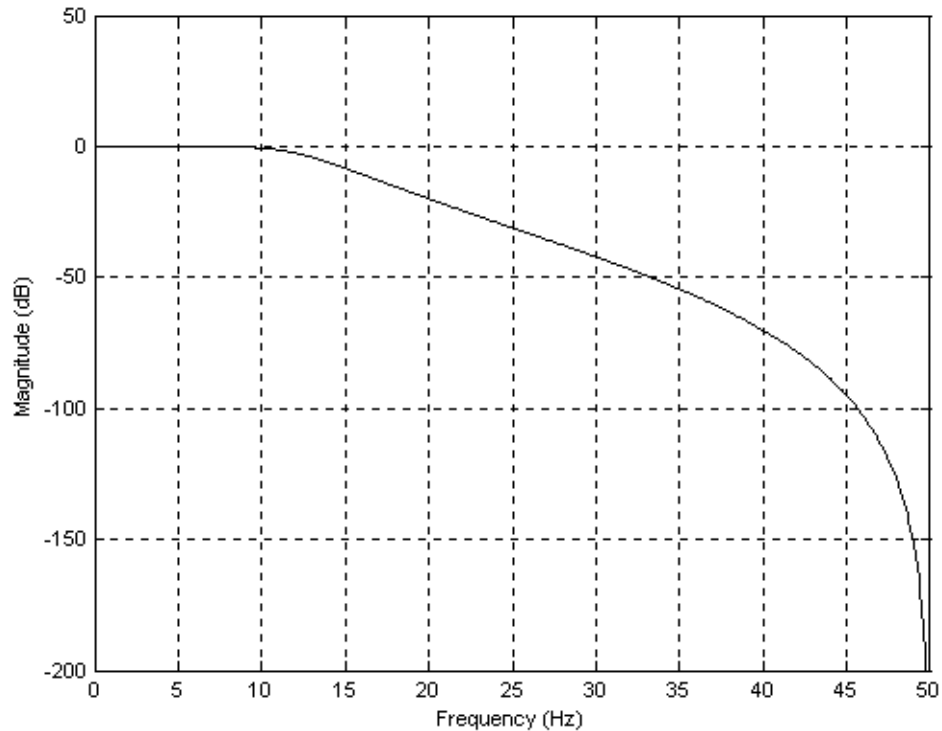
Fig. 7.2. Magnitude response of a low pass filter

Representative types of low pass filters are the moving average filter, the Butterworth filter, the Chebyshev filter, and the elliptic filter [58]-[60]. The filters that are considered in this research work are the moving average filter and the Butterworth filter. Chebyshev and elliptic filters have similar characteristics to Butterworth filters but have considerable ripple in their passbands. A passband is the region where the filter allows the frequency components to pass through. Therefore, the frequencies that will be allowed to pass through the filter will be amplified by different amounts. This nonuniform change in the magnitude of the frequencies of each signal may cause inaccuracies during the estimation process.

The moving average filter in the discrete time domain is given by [58],

$$y_n = \frac{1}{N}\sum_{i=0}^{N-1}x_{n-i} \; , \tag{7.1}$$

where x_{n-i} are the input data and N is the degree of the moving average.   After transforming (7.1) into the z-domain, the transfer function of an N-point moving average is given by,

$$H(e^{j\omega\Delta T}) = \frac{1}{N}\sum_{i=0}^{N-1}e^{-ji\omega\Delta T} \; . \tag{7.2}$$

The moving average filter is the fastest digital filter available and an exceptionally good smoothing filter in the time domain.   Moreover, it is relatively easy to program. However, it has a slow roll off, which may allow some frequencies to pass through. Further, significant attenuation may occur within the frequency range of interest while its frequency domain filtering qualities are not so admirable.   A model of a moving average filter is shown in Fig. 7.3.   The magnitude and phase responses of a 40 point moving average filter for a signal that has a time step between measurements of 0.1 ms is shown in Figs 7.4 and 7.5.
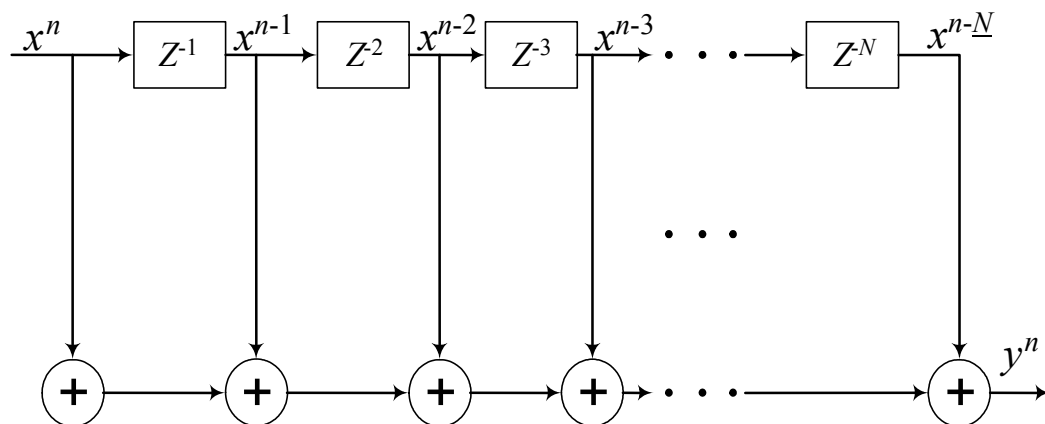
Fig. 7.3. Moving average filter implementation
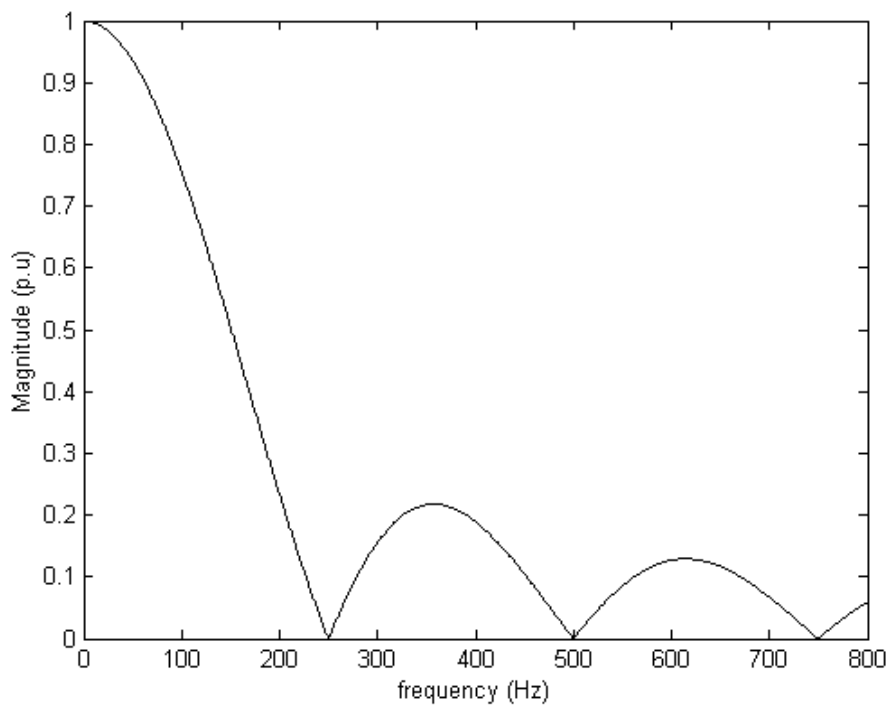
Fig. 7.4. Magnitude response of a moving average filter
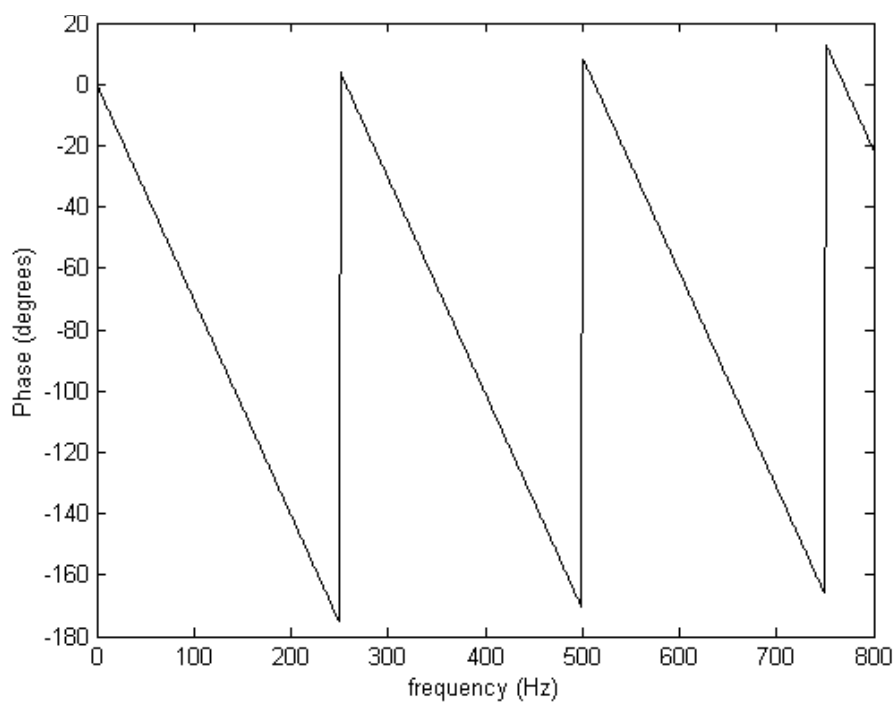
Fig. 7.5. Phase response of a moving average filter

The moving average filter in this research work is used as a supplementary filter for signals that do not require excessive filtering or for signals that require a slight improvement before filtering with the Butterworth filter.

The second type of low pass filter considered is the Butterworth filter. This filter belongs to the category of infinite impulse response (IIR) digital filters. IIR filters have input-output characteristics that are governed by linear difference equations with constant coefficients [115]. Further, these difference equations are recursive since each value of the filtered signal is computed using previously computed values of the filtered signal. Finite impulse response (FIR) filters on the other hand, use only values of the unfiltered signal to compute the values of the filtered signal, and are thus non-recursive filters. IIR filters have the advantage over FIR filters that they can meet the given specifications with a lower order filter because of the recursive differential equations that are used in the filter implementation.

The Butterworth filter is considerably more difficult to program but it has a good transient response and a fast roll off. The general N^{th} order Butterworth filter has a magnitude squared function in the discrete case [59],

$$|H(j\Omega)|^2 = \frac{1}{1+(j\Omega/j\Omega_c)^{2N}}, \tag{7.3}$$

where Ω_c is the cutoff frequency. The cutoff frequency is the frequency where the magnitude of the filter is 3 dB below the maximum magnitude in the passband region. As N increases, the frequency response becomes sharper. However, at the cutoff

frequency the magnitude of the transfer function is $1/\sqrt{2}$ for every value of N. The

Butterworth filter is an all pole filter and has a transfer function of the form [60],

$$H(s) = \frac{Kb_0}{s^n + b_{n-1}s^{n-1} + \cdots + b_1 s + b_0} , \qquad (7.4)$$

where K is a constant and b_i are constant design coefficients. An example of an

implementation of the Butterworth filter is shown in Fig. 7.6. This implementation has a

first order section followed by a second order section.
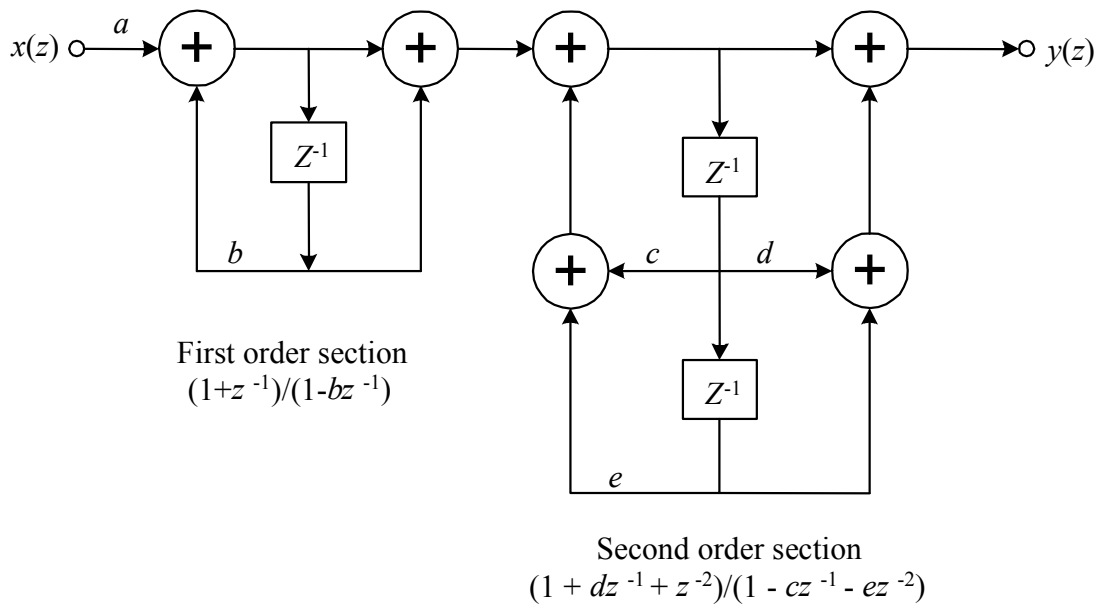
Fig. 7.6. Cascade implementation of a low pass Butterworth digital filter [115]

Fig. 7.7 depicts the frequency response of a Butterworth filter with a cutoff

frequency of 20 Hz, a stopband frequency of 200 Hz, a permissible passband ripple of 0.1

dB, and a stopband attenuation of 20 dB. The stopband frequency is the frequency

beyond which the magnitude of a low pass filter approaches zero in order to eliminate the frequency components in the stopband region.
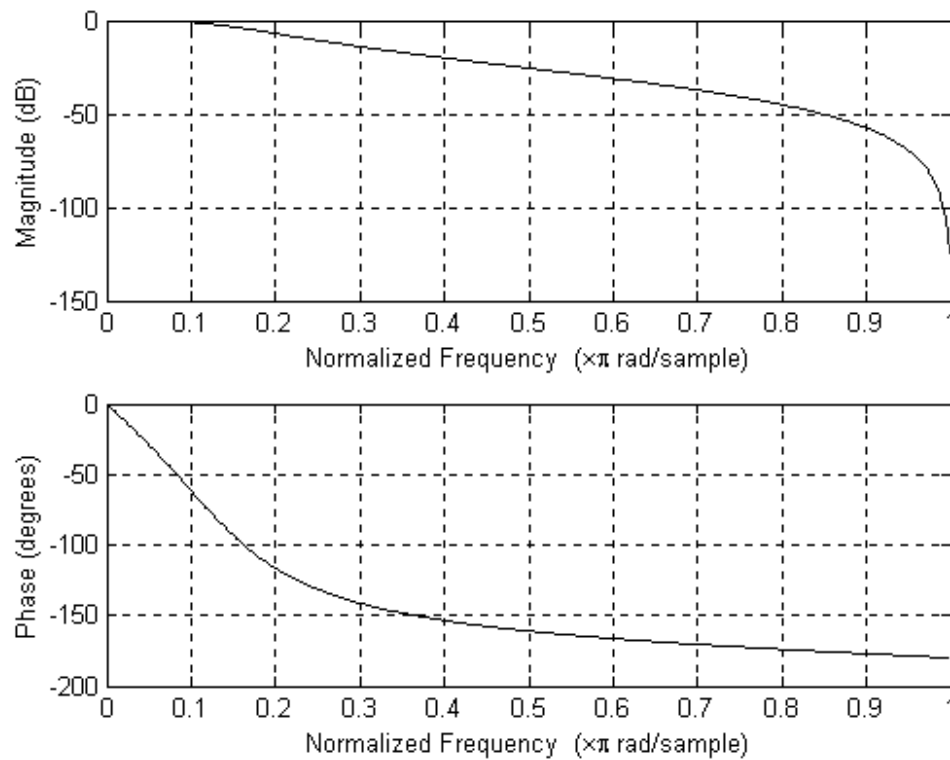
Fig. 7.7. Frequency response of a sample Butterworth filter

From the frequency response of Fig. 7.7 it can be observed that the passband magnitude is maximally flat and therefore all the frequency components in the passband region will be unscathed from the filtering process (or at worst they will be all attenuated by the same amount). On the other hand, the frequency components in the two regions following the passband (the transition band and the stopband) will be attenuated depending on the magnitude of the response at those frequencies.

Observation of the phase response shows that the frequency components in the passband region may not experience the same amount of phase delay. Although the signals under consideration in this research work are DC signals and this would not have a considerable effect on them, some of the transient behavior of the synchronous generator might be altered by changing the phase of the small frequency components in the vicinity of DC. Therefore, it is desired to use a filter that introduces no phase shift during the filtering process. This is achieved by performing a zero phase digital filtering [59], [61]-[63]. The idea behind zero phase digital filtering is to filter the signal in the forward direction and then reverse the filtered sequence and perform the filtering process in the reverse direction. The resulting sequence has zero phase distortion and twice the filter order.

The resulting recursive equation of a zero phase digital filter is of the form,

$$y[n] = b_0 x[n] + b_1 x[n-1] + \cdots + b_{nb} x[n-nb]$$
$$- a_2 y[n-1] - a_3 y[n-2] - \cdots a_{na} y[n-na], \tag{7.5}$$

where na and nb are the lengths of the coefficient vectors a and b respectively, and n is the order of the filter. x and y are the unfiltered and filtered signals respectively.

During the course of the filtering of the actual signals obtained from the synchronous generator, it was found that a single Butterworth filter was not sufficient to filter all noisy frequency components successfully. This is due to the limitations that are imposed on every filter because of the stability requirements. Designing any filter that is maximally flat in the vicinity of DC and at the same time attenuating sharply all frequency components beyond a frequency close to DC (for example 10 Hz) is

unrealistic. The resulting filter would be unstable and certainly the filtered signal would bear no resemblance to the original signal.

As will be shown in the frequency responses of all the measured signals in the next section, there is no clear separation between the actual signal and the noise content. Consequently, the transition band, during which the magnitude response of the filter is allowed to attenuate, is basically nonexistent. Therefore, a stable low pass filter will attenuate all high frequency components successfully, but will not attenuate the low frequency noisy components in a satisfactory manner.

As a solution to this problem, all the designed filtering processes used in this research work utilize a variable number of Butterworth filters depending on the noise content and the frequency distribution of the noise for each signal. The proposed method is thus referred to as multiple parallel filtering. Multiple parallel filtering in effect applies the same stable Butterworth filter (or any other filter of choice), to slowly attenuate all frequency components that are located in the transition band. The result of each subsequent filter is a frequency spectrum whose noisy content is attenuated little by little until the desired result is achieved.

Fig. 7.8 illustrates the idea of multiple parallel filtering using a number of parallel identical Butterworth filters. In this example, each filter has a cutoff frequency of 100 Hz and a stopband frequency of 800 Hz selected so as to show the slight improvement of each subsequent filter. Fig. 7.8(a) shows the unfiltered signal, while Fig. 7.8(b) shows the signal after the application of the first Butterworth filter. Figs 7.8(c) and (d) show the signal after the application of the second and sixth Butterworth filters respectively. The

magnitude of the high frequency components reduces after the application of each low pass filter. At the end of the filtering process the high frequency components are minimized.
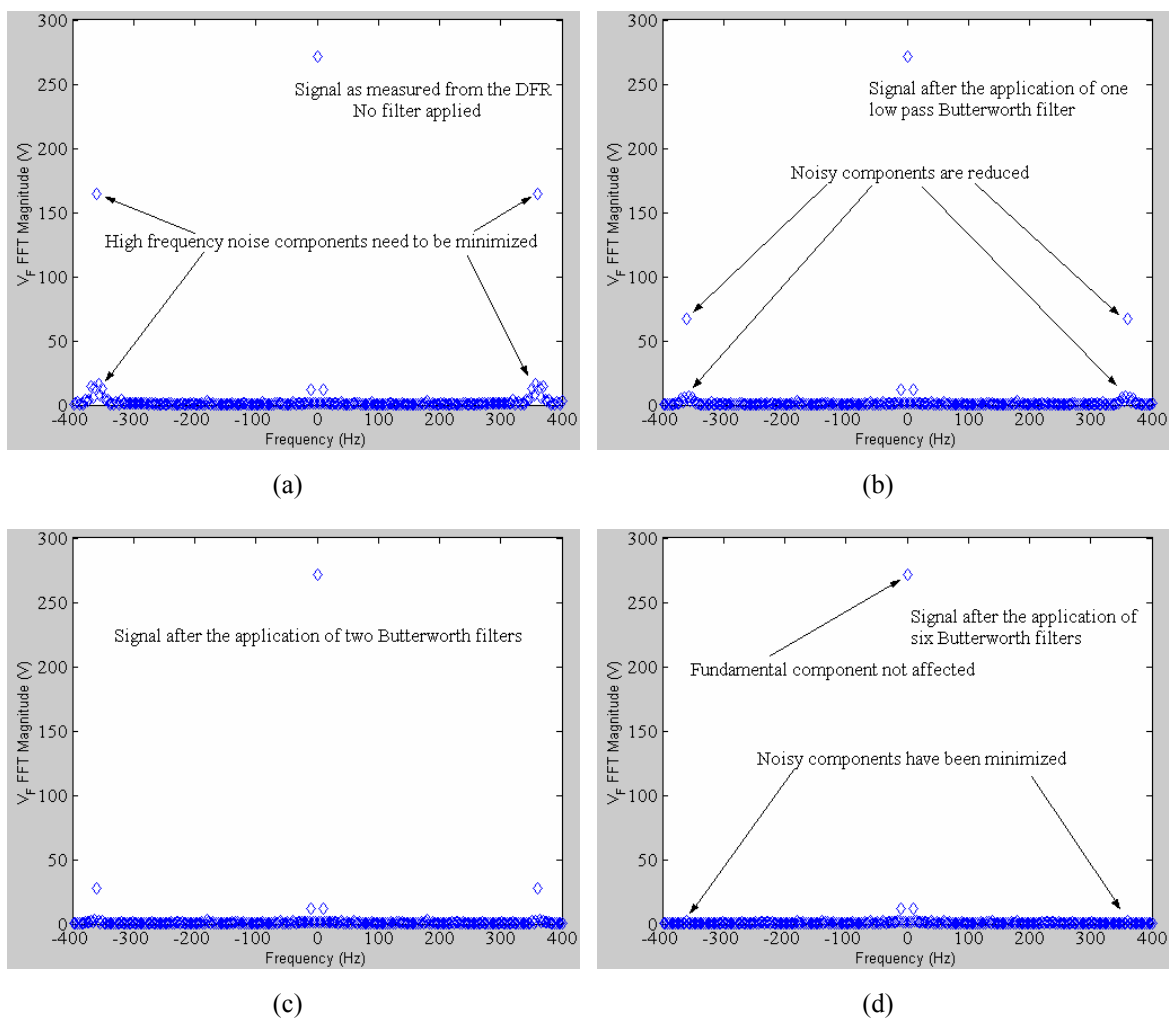
Fig. 7.8. Example of a multiple parallel filtering method for the successive attenuation of transition band frequency components

7.3 Filtering of the field measurements

The stator and rotor measurements are filtered using two separate algorithms because of differences between the measurement of the two types of signals by the recording instrument. In this section, the filtering of DFR measured rotor (field) quantities for the generator under consideration is described. The filtering of stator measurements is relegated to Section 7.4. A specific case is considered to demonstrate the filtering of both the field and stator signals, as well as the estimation of the parameters in Section 8.2. The generator for the case under consideration is FC5HP located at the Four Corners Generating Station of the Arizona Public Service Company (APS). The generator is operating at the steady state; the active power at the terminals of the generator is 142.2 MW and the reactive power is 3.7 MVAr at a lagging power factor. The data used throughout this chapter are obtained from measurements at the terminals of the synchronous generator while it is serving its load.

The field voltage and current are slowly varying DC signals. They are measured through a six pulse rectifier and thus their time plots have a rather unusual appearance as shown in Figs 7.9 and 7.10. An examination of the frequency spectrum of the two signals as shown in Figs 7.11 and 7.12 indicates that both signals (and especially the voltage) are highly corrupted with high frequency components. In the case of the frequency spectrum of the current as seen in Fig. 7.12, the main frequency component can be seen clearly at the center of the plot. Other frequency components are very small and can be seen at lower magnitudes. The apparent overlapping of frequency components is due to the choice of the dimensions of the horizontal axis and the size of

the elements used to mark each frequency point. The high frequency components for both the voltage and the current need to be minimized to obtain the actual DC signals. It should be noted that the frequency spectrum in both graphs and in subsequent graphs in the rest of the chapter is shifted so that the zero frequency component is at the middle of the spectrum. Further, where applicable, the frequency spectrum is truncated to show only the frequencies of interest or to enable the visualization of the spectrum more clearly. The frequency components of a signal in general range up to the Nyquist frequency which is half of the sampling frequency. The Nyquist frequency for the signals under consideration in this chapter is 5 kHz.
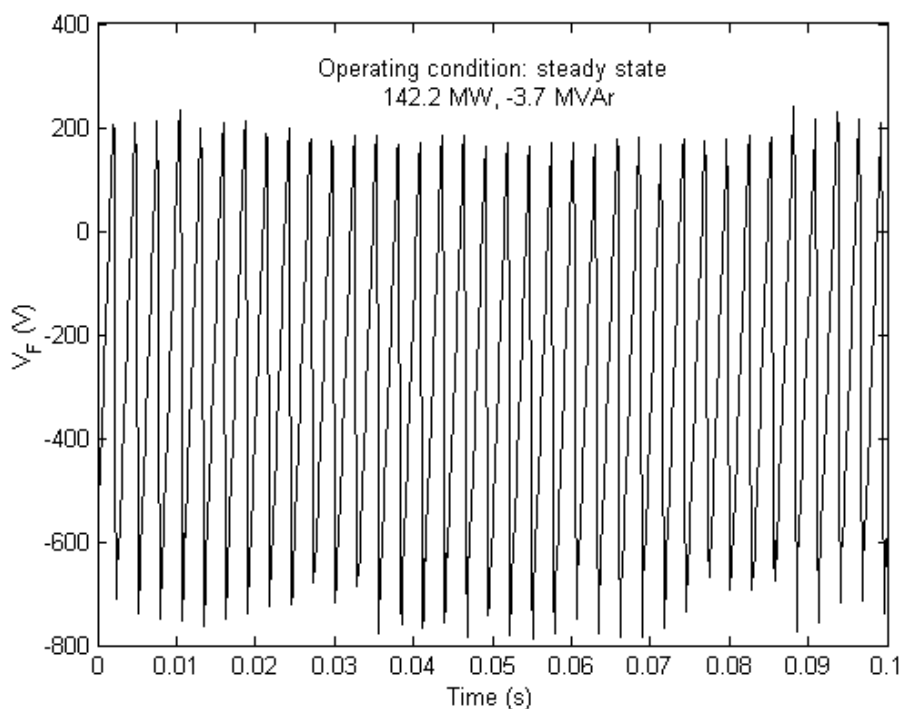
Fig. 7.9. Time domain field voltage for generator FC5HP as measured by a DFR
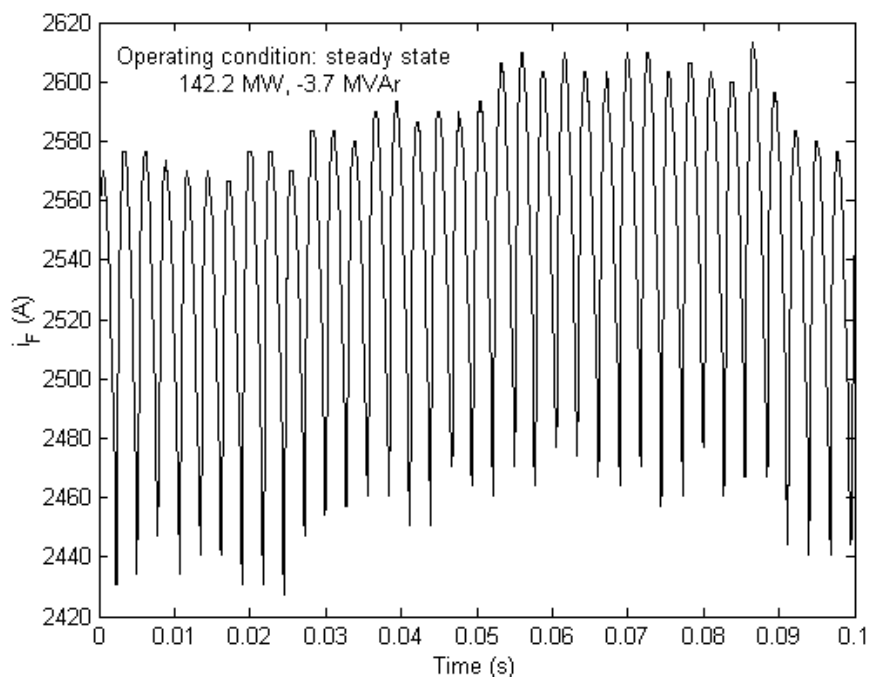
Fig. 7.10. Time domain field current for generator FC5HP as measured by a DFR
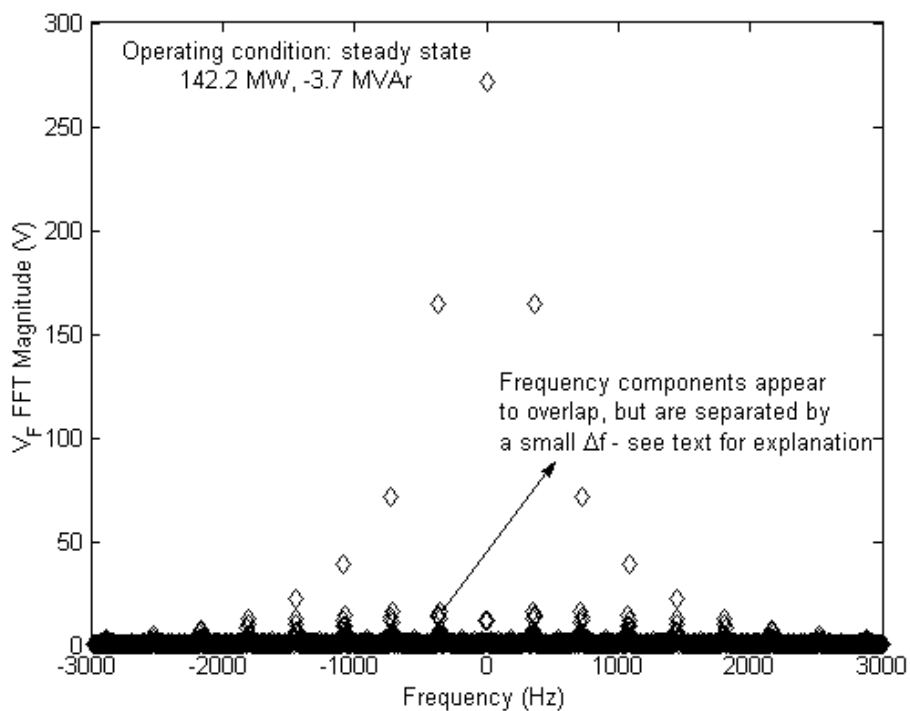
Fig. 7.11. Frequency spectrum of the field voltage for generator FC5HP
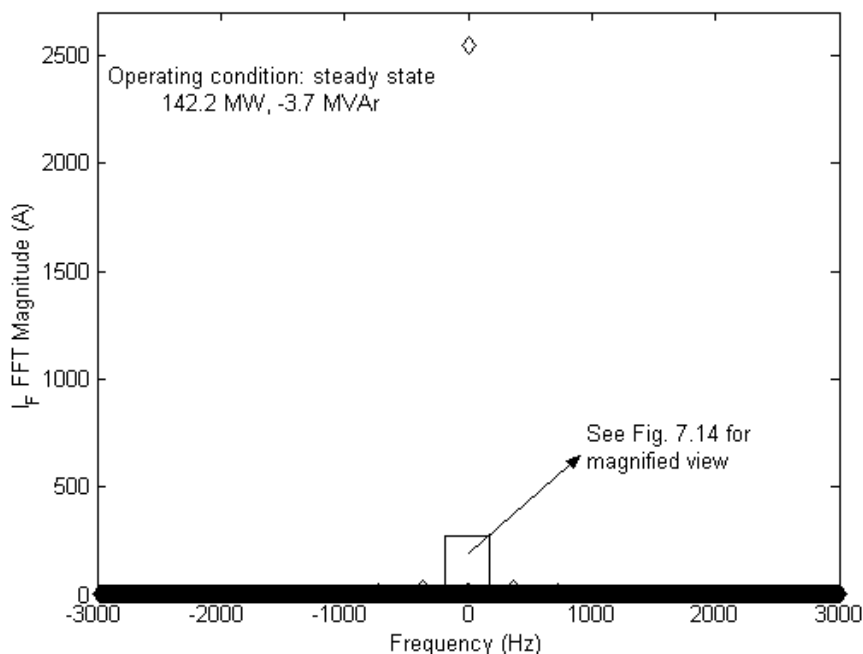
Fig. 7.12. Frequency spectrum of the field current for generator FC5HP

Considering the field current, a multiple parallel Butterworth filtering process transforms the measured field current (whose main noise components are shown in Fig. 7.13) into a DC-like signal after the removal of high frequency components. The same frequency components are depicted in Fig. 7.14 after the filtering process. The final filtered signal in the time domain can be seen in Fig. 7.15.

A comparison of the ripple in the original DFR measured field current and in the filtered field current as a percentage of the DC component of the signal, is an indication of the effect of filtering on the field current. The ripple can be calculated by dividing the difference of the maximum and minimum values of a signal by the DC value of the signal. In the case of the unfiltered signal of Fig. 7.10, the ripple is calculated to be 7.7%, while in the case of the filtered signal of Fig. 7.15, the ripple is 1.7%. The filtering process for the field voltage is similar to that of the field current and will not be repeated.
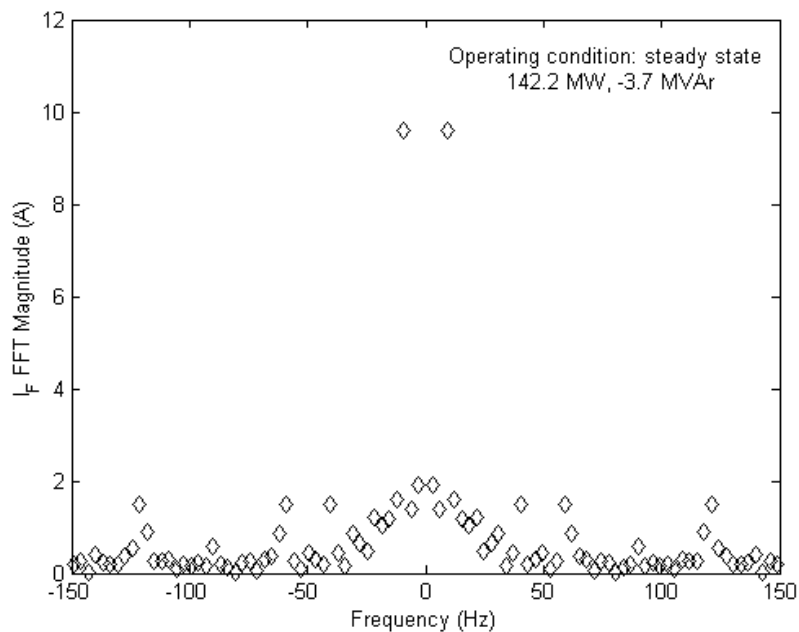
Fig. 7.13. Frequency spectrum in the vicinity of DC for the DFR measured field current

for generator FC5HP
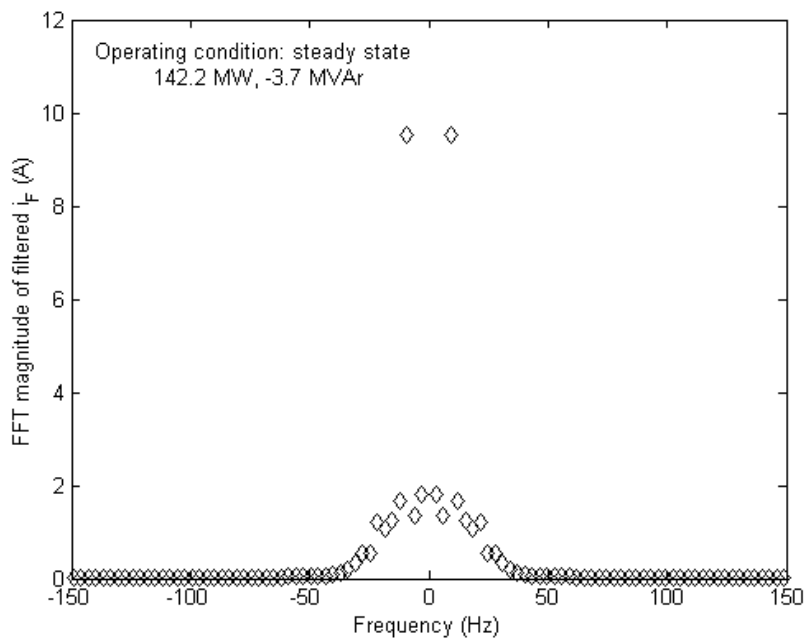
Fig. 7.14. Frequency spectrum in the vicinity of DC for the filtered field current for
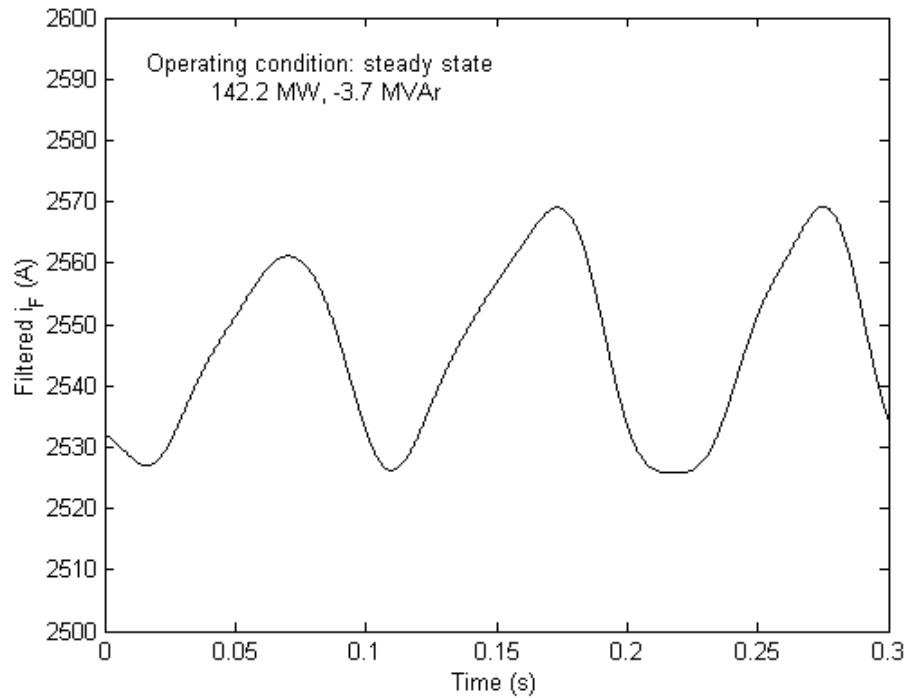
generator FC5HP

Fig. 7.15. Time domain filtered field current for generator FC5HP

7.4 Filtering of the stator measurements

The measurements obtained from the stator terminals of the synchronous generator are the three line-to-line voltages v_{ab}, v_{bc}, and v_{ca} and the three currents i_a, i_b, and i_c. These signals do not have the complications that are associated with the field signals as shown in the previous section, but they still contain a certain amount of noise that needs to be removed in order to optimize the performance of the estimator.

The filtering process for the stator measurements is performed after the calculation of the phase voltages and after the transformation of the *abc* voltages and currents into *0dq* signals through Park's transformation as illustrated in Chapter 2. A possible concern in any type of measurements is the presence of outliers or inconsistent

data. Such outliers appear in the form of spikes in the time domain plot of each signal. Outliers are caused by metering errors and can be safely removed without risking inaccuracies in the estimation process. Therefore, prior to the filtering of high frequency components in any signal, a bad data detection and rejection algorithm is implemented to remove outliers.

The process followed for this algorithm is first to detect a spike in any of the signals by browsing through all the measurements obtained for each signal. For the purposes of this application, a spike is defined to be greater than 10% of the value of the signal at the previous step. Due to the small time constants of synchronous generators, none of the measurements can vary by 10% or more within two consecutive steps even in the transient case. The only possibility for such a variation is if the generator experiences a short circuit fault. However, the detection algorithm is able to check for such a possibility and keep the measurement as is. If a spike in any one signal is detected, then the whole data set for that time step is removed.

After the implementation of the bad data detection and rejection algorithm, a multiple parallel filtering process is implemented similar to the description in the previous section. Filter characteristics are chosen depending on the location and on the size of the noisy frequency components, but in general, the filters for all the signals have a cutoff frequency of approximately 10 Hz and a stopband frequency of 100 Hz with a stopband attenuation of about 60-80 dB. This general characteristic for a noise filter enables the automatic filtering of signals from any synchronous generator without the need to examine each of the signals individually.

As an example, the filtering process of the direct axis voltage (v_d) will be demonstrated. Again, in this section, all measurements depicted are for the same 483 MVA synchronous generator considered in the previous section and in Chapter 6 and Appendix A. Fig. 7.16 depicts the time domain signal of v_d as calculated by the combination of the phase voltages of the generator through Park's transformation. v_d is expected to be a DC signal (or a slowly varying signal). Observation of Fig. 7.16 shows a rather noisy signal as well as an outlier in the form of a spike. A portion of the frequency content of v_d is shown in Fig. 7.17. The zero frequency component is not shown in order to focus on the frequency components of interest.
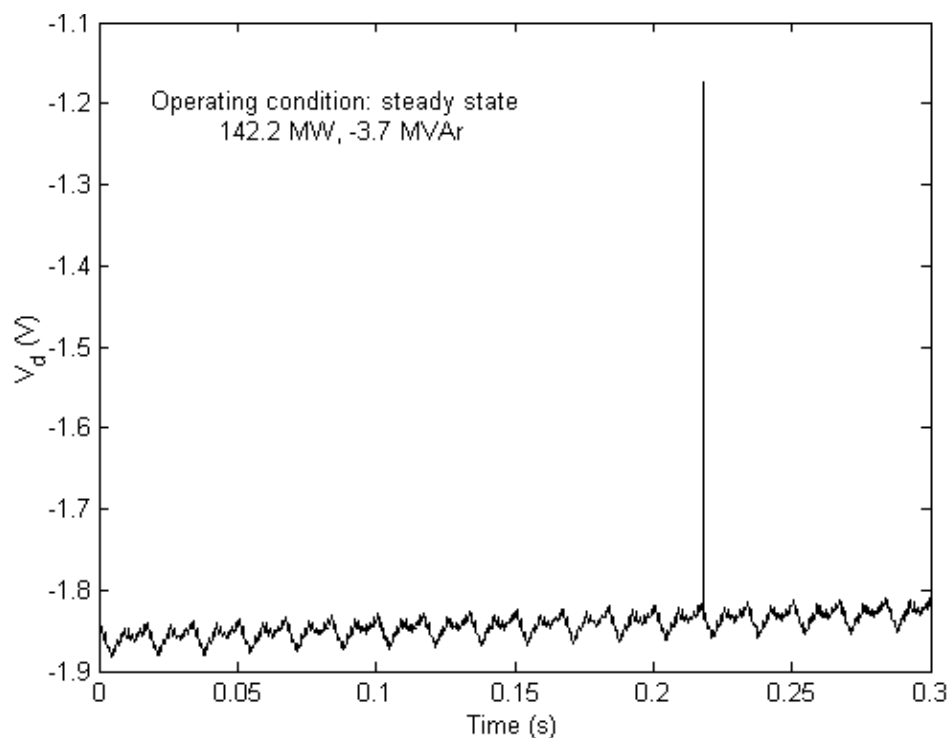
Fig. 7.16. Unfiltered *d* axis voltage in the time domain for generator FC5HP
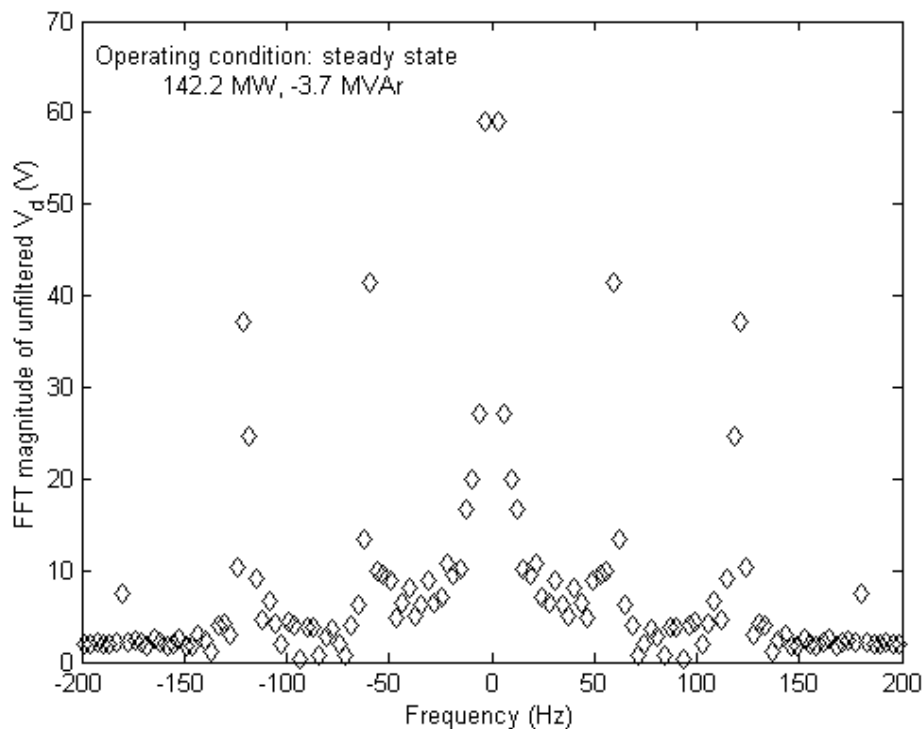
Fig. 7.17. Frequency content of the *d* axis voltage for generator FC5HP before filtering

(zero frequency component not shown)

The result of the implementation of the bad data detection and rejection algorithm and the filtering process can be observed in Figs 7.18 and 7.19. It can be seen that the majority of the noisy frequency components have been eliminated or reduced significantly. Frequency components in the vicinity of DC are retained to track possible transient behavior of the generator. The resulting time domain signal shows both the removal of the spike and the DC nature of the signal. The filtering process for all other stator signals is identical to the one described in this section for v_d.
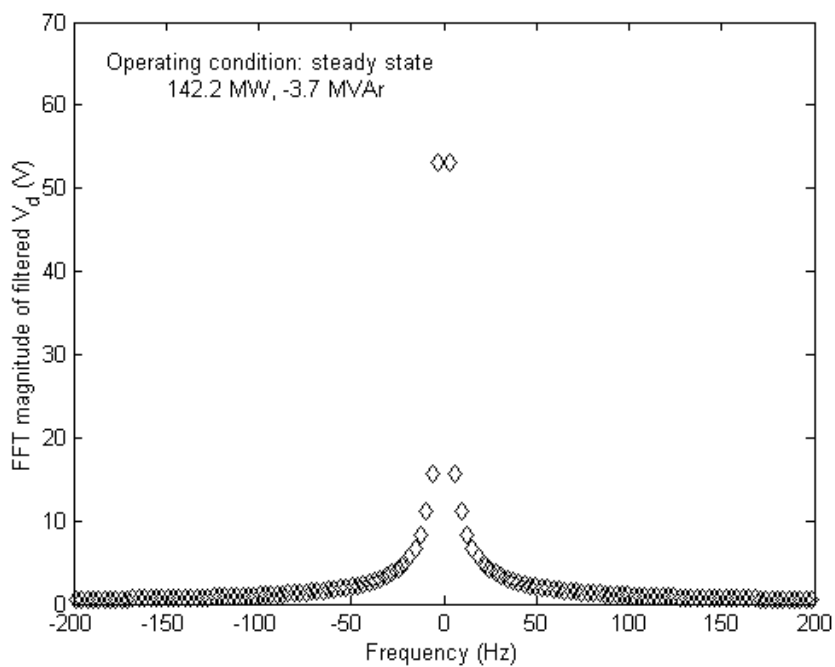
Fig. 7.18. Frequency content of the *d* axis voltage for generator FC5HP after filtering
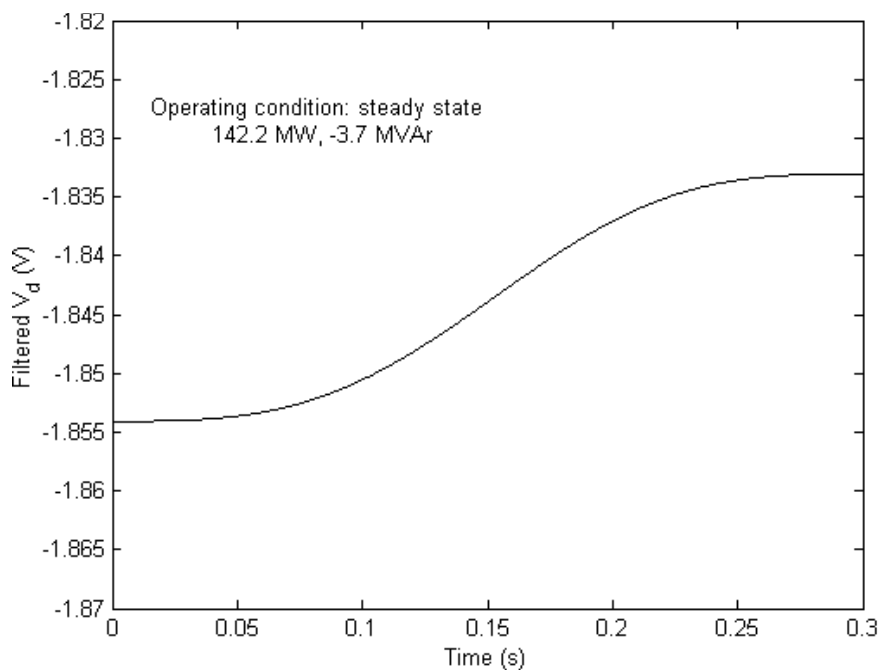
Fig. 7.19. *d* axis voltage in the time domain after spike and noise filters are applied for

generator FC5HP

7.5 Summary

This chapter concentrated on the filtering of the measurements prior to the implementation of the estimation algorithm. The filtering process comprises the removal of inconsistent measurements (outliers) and the minimization of high frequency noise components. All filtered signals are DC signals (or transformed DC signals) and appropriate low pass filters were utilized to remove noise components above certain frequencies. Low frequency components were retained to capture possible slow variations in the behavior of the signals.

The filters used for the purposes of this application were the Butterworth and moving average filters. Other filters such as the Elliptic and Chebychev filters were considered but not implemented because they were inferior in performance to the other available filters.

The filtering of rotor and stator signals was considered separately in Sections 7.3 and 7.4 respectively. Case study results indicate satisfactory performance of the filters, rejection of bad data, and minimization of the noise in measurements. Finally, a new approach to filtering was introduced: multiple parallel filtering. This approach enables the application of successive identical filters to slowly attenuate high frequency components without affecting the components of interest. A single low pass filter would not perform successfully in this application because of the characteristics of the signal under study. It is not possible to design a single filter with both a low cutoff frequency and a high attenuation, since an unstable filter results. Multiple parallel filtering allows

the minimization of high frequency components and medium frequency components by using successive stable filters that have a low attenuation.

CHAPTER 8

PARAMETER ESTIMATION FROM ACTUAL MEASUREMENTS

8.1 Introduction

Implementation of any proposed algorithm using actual measurements is the ultimate test for its viability and applicability to the system under study. After the successful testing of the parameter estimation algorithm using both synthetic and EMTP data as demonstrated in Chapter 6, it is necessary to test the estimator using data obtained from synchronous generators and observe whether the proposed method agrees to the practical results.

Synchronous generator measurements for the purpose of this research work are obtained through a digital fault recorder (DFR). A DFR is effectively a data acquisition system that is used to monitor the performance of generation and transmission equipment, and therefore is connected permanently to utility generators. DFRs are typically used by the majority of the utilities to monitor the operation of generators. For this particular estimation methodology, the measurements are obtained at the terminals of committed synchronous generators (the units serve their typical loads). Different operating levels are considered to examine the accuracy of the proposed method with varying degrees of excitation and different saturation levels. The measurements are stored in a data file that can be read by the estimator. The data files are typically of the COMTRADE data file format [116], which is an approved IEEE data format for storage of measurements. The data can either be in ASCII format or binary format. A short description of the COMTRADE data format that is also supported by the designed estimator is given in Appendix E.

In between the data acquisition and the estimator implementation there are a number of other processes that need to be performed to prepare the data in a form that can be used by the estimator. Fig. 8.1 shows a flowchart of the procedure followed to perform the parameter estimation. The measurements obtained for the stator voltages are sometimes line to line measurements, and therefore it may be necessary to transform these signals into phase quantities. Further, the power angle δ needs to be calculated in order to perform the Park's transformation as explained in Chapter 2. The above transformations and the procedure as illustrated in Fig. 8.1 are shown in detail in Appendices G and H as used in the code of the estimator.

8.2 Results of parameter estimation from actual measurements

The last part of the system identification procedure is the parameter estimation from the filtered measurements. The estimator configuration follows the procedure described in Section 5.6 and the procedure followed in the parameter estimation from EMTP simulated measurements of Chapter 6. The estimation of parameters from EMTP measurements did not clearly distinguish the dominant model between the proposed models (models 2.1, 2.2, and 2.2x), and therefore all three models will be tested with actual measurements.

In contrast to the simulated data set, an examination of the actual data sets obtained from the synchronous generator terminals and used for the parameter estimation described in this section, indicates that the generators operate within the saturation region. Therefore, the estimator algorithm needs to adjust the parameters for saturation

as explained in Chapter 3. The parameters obtained from the estimator reflect the true state of the system including saturation.

```
                    ┌─────────────┐
                    │   START     │
                    └─────────────┘
                           │
                           ▼
              ╱ Obtain stator (abc)  ╱
             ╱  measurements and    ╱
            ╱   field measurements ╱
                           │
                           ▼
              ╱ Obtain MVA and      ╱
             ╱  kV base and        ╱
            ╱   known parameters  ╱
                           │
                           ▼
          ┌──────────────────────────┐
          │ Filter high frequency noise in │
          │   field voltage and current    │
          └──────────────────────────┘
                           │
                           ▼
          ┌──────────────────────────┐
          │ Calculate active and reactive power │
          │  and power factor at each point     │
          └──────────────────────────┘
                           │
                           ▼
          ┌──────────────────────────┐
          │  Convert line-line voltages │
          │     to phase voltages       │
          └──────────────────────────┘
                           │
                           ▼
          ┌──────────────────────────┐
          │ Calculate the power angle δ │
          └──────────────────────────┘
                           │
                           ▼
          ┌──────────────────────────┐
          │ Perform Park's transformation │
          │   to convert abc to 0dq       │
          └──────────────────────────┘
```

Second column:

- Reject outliers in stator measurements
- Filter high frequency noise in stator measurements
- Convert all measurements to per unit quantities
- Calculate derivatives of currents
- Implement observer for damper winding currents
- Estimate generator parameters
- END

Fig. 8.1. Algorithm for estimator implementation for actual measurements

Table 8.1 depicts the estimated parameters in each of the three proposed models using actual measurements from generator FC5HP (case study R-NC-01-10). All parameters are individually estimated assuming that all other parameters are known. In the case of model 2.2x, L_{AD} and L_{AQ} are the only parameters affected by saturation since all other inductances have been expressed in terms of these mutual inductances according to (3.11). In the case of models 2.1 and 2.2 a number of parameters is affected by saturation and these parameters are adjusted prior to the estimation procedure if they are not desired to be estimated. Therefore, Table 8.1 depicts the saturated values of the parameters (where applicable).

TABLE 8.1

Estimated parameters for the three proposed models for generator FC5HP

(case study R-NC-01-10)

Parameter (p.u.)	Model 2.1	Model 2.2	Model 2.2x
L_d	1.6146	1.6147	N/A
L_q	1.5648	1.5794	N/A
L_F	1.49493	1.49493	N/A
kM_F	1.5355	1.5355	N/A
L_{AD}	N/A	N/A	1.5963
L_{AQ}	N/A	N/A	1.4057
r	-0.0061185	-0.01273	-0.01273
r_F	$8.386x10^{-4}$	$8.386x10^{-4}$	$8.386x10^{-4}$

As mentioned above, the estimated inductances of Table 8.1 potentially reflect the true state of the system including the effect of saturation. Since the exact values of the parameters at every operating point are not known, it is not possible to derive any definite conclusions about the accuracy of the estimated parameters. Therefore, it is desired to nullify the effect of saturation by applying the inverse of the appropriate saturation factor to each of the saturated inductances. This will offer estimates of the unsaturated inductances and a comparison to the manufacturer values may be obtained. However, the manufacturer values of the parameters have been calculated by off-line tests and testing methods that may not necessarily reflect the operating point under consideration. Moreover, manufacturer values are typically design values for a series of manufactured generators, and consequently differences between designed and actual parameter values do exist. Therefore, the percent difference between the estimated parameters and the manufacturer parameters cannot be classified as a percent error as in the case of the simulated measurements. The difference between the estimates and their "nominal" values is referred to as a percent deviation. The percent deviation cannot be used as a verification or rejection of the proposed method, but it can offer an insight as to whether the estimates obtained are reasonable or not. In general, it is more important to have consistency in the estimated parameters between various data sets from the same generator, than to have results with varying degrees of accuracy.

Table 8.2 depicts the percent deviation of the estimated parameters from the manufacturer suggested values for the parameters, after the effect of saturation has been nullified to obtain an estimate of the unsaturated values of the inductances. All three

models are considered to enable comparison of the estimation method between all the candidate models.

TABLE 8.2

Calculation of unsaturated parameters from the estimated parameters of generator FC5HP

(case study R-NC-01-10)

Parameter	Manufacturer value (p.u.)	Model 2.1		Model 2.2		Model 2.2x	
		Estimated parameter (p.u.)	% Deviation	Estimated parameter (p.u.)	% Deviation	Estimated parameter (p.u.)	% Deviation
L_d	1.80	1.757	2.4	1.757	2.4	N/A	N/A
L_q	1.72	1.702	1.0	1.724	0.2	N/A	N/A
L_F	1.75791	1.627	7.4	1.627	7.4	N/A	N/A
kM_F	1.64	1.671	1.9	1.671	1.9	N/A	N/A
L_{AD}	1.64	N/A	N/A	N/A	N/A	1.737	5.9
L_{AQ}	1.56	N/A	N/A	N/A	N/A	1.529	2.0
r	0.0046	-0.00612	233	-0.01273	377	-0.01273	377
r_F	$8.454x10^{-4}$	$8.386x10^{-4}$	0.8	$8.386x10^{-4}$	0.8	$8.386x10^{-4}$	0.8

Table 8.2 shows that the results obtained from all three models are similar. Results from models 2.2 and 2.2x are slightly improved due to the more accurate modeling of the quadrature axis. A discussion for some of the results from the three models is appropriate at this point. The field resistance is estimated with a deviation of 0.8% in all three models. Estimation of the field resistance is a critical aspect of the

overall estimation procedure since one of the motivations for this research work is the tracking of the change in the field resistance to detect and prevent short circuits in the field winding. The nominal field winding resistance noted as the manufacturer value in Table 8.2 is an approximate quantity since the generator under consideration has been rewound a number of times because of short circuits in the field winding. Therefore, no definite comparison can be performed between the estimated and the nominal value. Nevertheless, the estimation procedure gains considerable confidence from these results since the deviation between the two values is very small.

Values for L_d, L_q, and kM_F are estimated within a reasonable accuracy in both models 2.1 and 2.2, with L_q being estimated more accurately in model 2.2. The percent deviations for these parameters vary from 0.2 to 2.4%. In the case of the field inductance L_F, the percent deviation attained is in the order of 7.4%. This result is not considered satisfactory, but similarly to the case of the field resistance, the nominal value of L_F may not be accurate because of the rewinding of the field winding of this particular generator.

In the case of model 2.2x, L_{AQ} is estimated with a deviation of 2.0% from its nominal value, while L_{AD} is estimated with a deviation of 5.9%. A portion of the deviation of L_{AD} can be attributed to the field inductance L_F, since in model 2.2x the field inductance was expressed as $L_F = L_{AD} + l_F$, where l_F is the leakage inductance of the field winding. Therefore, the estimated L_{AD} will reflect any possible inaccuracy of l_F because of the rewinding of the field winding.

Finally, the results for the stator resistance in all three models show that currently the stator resistance cannot be estimated accurately. The amount of noise in the

measurements and the representation of saturation are two of the reasons for the inaccuracy in the stator resistance. A number of case studies were performed to observe how using different saturation factors and various filtering mechanisms affect the stator resistance. For example, if no saturation is modeled, then the estimated stator resistance was positive and much higher than the manufacturer value of r. As saturation factors of increasing values were introduced to adjust L_{AD} and L_{AQ}, the value of the stator resistance reduced and in some cases the estimated value was negative as in the case of Table 8.2. The inability to estimate r within a satisfactory degree of accuracy is not an obstacle to this method of estimation. Typically, there is no interest in estimating r. The main parameters of interest are L_d, L_q (or L_{AD} and L_{AQ}), and r_F.

8.3 Multiple parameter estimation

Multiple parameter estimation from actual measurements is an important aspect of the estimator. In many cases (like the one under consideration in this research work) it is possible that there is uncertainty in more than one parameter. Therefore it is imperative that the feasibility of multiple parameter estimation is investigated. Ideally, it is desired that the percent deviation obtained for each parameter is the same in both individual parameter estimation and multiple parameter estimation.

Two case studies are performed. In the first case study (R-NC-03-11), L_d, L_q, and r_F are estimated simultaneously for models 2.1 and 2.2, while L_{AD}, L_{AQ}, and r_F are estimated simultaneously for model 2.2x. The estimated parameters are depicted in Table 8.3, while the unsaturated parameters calculated from the estimated parameters are

depicted in Table 8.4. It can be observed that for all three models the estimated parameters and their percent deviations are identical to the corresponding parameters in the individual parameter estimation of Table 8.1 and Table 8.2.

TABLE 8.3

Multiple simultaneous parameter estimation for generator FC5HP (case study R-NC-03-11)

Parameter (p.u.)	Model 2.1	Model 2.2	Model 2.2x
L_d	1.6146	1.6147	N/A
L_q	1.5648	1.5794	N/A
L_{AD}	N/A	N/A	1.5963
L_{AQ}	N/A	N/A	1.4057
r_F	$8.386x10^{-4}$	$8.386x10^{-4}$	$8.386x10^{-4}$

TABLE 8.4

Calculation of unsaturated parameters for generator FC5HP (case study R-NC-03-11)

Parameter	Manufacturer value (p.u.)	Model 2.1		Model 2.2		Model 2.2x	
		Estimated parameter (p.u.)	% Deviation	Estimated parameter (p.u.)	% Deviation	Estimated parameter (p.u.)	% Deviation
L_d	1.80	1.757	2.4	1.757	2.4	N/A	N/A
L_q	1.72	1.702	1.0	1.724	0.3	N/A	N/A
L_{AD}	1.64	N/A	N/A	N/A	N/A	1.737	5.9
L_{AQ}	1.56	N/A	N/A	N/A	N/A	1.529	2.0
r_F	$8.454x10^{-4}$	$8.386x10^{-4}$	0.8	$8.386x10^{-4}$	0.8	$8.386x10^{-4}$	0.8

In the second case study (R-NC-03-12), L_d, L_q, and L_F are estimated simultaneously for models 2.1 and 2.2, while L_{AD}, L_{AQ}, and L_F are estimated simultaneously for model 2.2x.   The estimated parameters are depicted in Table 8.5, while the unsaturated parameters calculated from the estimated parameters are depicted in Table 8.6.   As in the previous case study, the estimated parameters and their percent deviations are identical to the corresponding parameters in the individual parameter estimation of Table 8.1 and Table 8.2.

TABLE 8.5

Multiple simultaneous parameter estimation for generator FC5HP

(case study R-NC-03-12)

Parameter	Model 2.1	Model 2.2	Model 2.2x
L_d	1.6146	1.6147	N/A
L_q	1.5648	1.5794	N/A
L_{AD}	N/A	N/A	1.5963
L_{AQ}	N/A	N/A	1.4057
L_F	1.49493	1.49493	N/A

The results of the multiple simultaneous parameter estimation case studies indicate that more than one parameter can be estimated at the same time. It was shown that there is no degradation of the percent deviation of the estimated parameters from their nominal values. Therefore, the confidence for the use of the estimator to estimate

multiple parameters simultaneously is reinforced. In case that the confidence in some of the synchronous generator parameters is limited (for example, because of alterations to the generator circuitry), multiple parameter estimation holds the key to a reliable estimation procedure.

TABLE 8.6

Calculation of unsaturated parameters for generator FC5HP (case study R-NC-03-12)

Parameter	Manufacturer value (p.u.)	Model 2.1		Model 2.2		Model 2.2x	
		Estimated parameter (p.u.)	% Deviation	Estimated parameter (p.u.)	% Deviation	Estimated parameter (p.u.)	% Deviation
L_d	1.80	1.757	2.4	1.757	2.1	N/A	N/A
L_q	1.72	1.702	1.0	1.724	0.3	N/A	N/A
L_{AD}	1.64	N/A	N/A	N/A	N/A	1.737	5.9
L_{AQ}	1.56	N/A	N/A	N/A	N/A	1.529	2.0
L_F	1.75791	1.627	7.4	1.627	7.4	N/A	N/A

8.4 Application of the algorithm to different machines and different operating points

Sections 8.2 and 8.3 discussed the parameter estimation procedure and some of the results obtained using measurements from generator FC5HP. It is necessary to perform parameter estimation for different generators and at different operating points to ensure that the method is applicable to other generators as well. Using measurements from different generators enables the examination of the accuracy of the proposed method, while the estimation at various operating points for each generator ensures that the results are consistent.

The case studies described in Sections 8.2 and 8.3 and a number of other case studies that were performed, permit the extraction of some conclusions pertaining to the model used in the estimation procedure. Clearly the estimates obtained from models 2.2 and 2.2x are superior to the ones obtained from model 2.1. This is due to the modeling of one extra damper winding in the quadrature axis of the generator; this winding causes the model to be symmetric with regards to the direct and quadrature axes. Results from models 2.2 and 2.2x are similar considering that the estimates of L_{AD} and L_{AQ} contain the error from the field winding inductance L_F and other quantities such as the mutual inductances between axes in the stator and the rotor (see (2.22), (3.11), and Table 6.2 for a comparison of the two models). A clear advantage of model 2.2x is that it offers an easier way of representing the magnetic saturation in a synchronous generator. Therefore, model 2.2x is the preferred model. The parameter estimation results presented in this section and in Appendix F are obtained through the utilization of model 2.2x.

Table 8.7 shows the parameter estimation results for ten data sets obtained from two identically designed units at the Redhawk generating station of APS. Eight of the data sets are obtained from GT1, while two of the data sets are obtained from GT2. Although the two units may have some differences in their parameters since no two units are exactly identical, the use of more data sets will allow the extraction of useful results pertaining to the accuracy of the method when applied to different generators and the representation of saturation. The two units are gas turbine units rated at 213.7 MVA and 18 kV. Their characteristics are described in Table 3.1.

TABLE 8.7

Parameter estimation results for Redhawk gas turbines 1 and 2*

Case study	Unit #	$\hat{L}_{AD}$ (p.u.)	$\hat{L}_{AQ}$ (p.u.)	$\hat{r}_F$ (p.u.)	K_{sd}	i_F (A)	P (MW)	Q (MVAr)	$\hat{L}_{ADu}$ (p.u.)	$\hat{L}_{AQu}$ (p.u.)	% deviation	
											L_{AD}	L_{AQ}
R-NC-03-13	GT1	1.5394	1.6787	$7.008x10^{-4}$	0.9479	1021.7	148.40	13.26	1.624	1.771	8.8	4.7
R-NC-03-14	GT1	1.6073	1.6735	$7.020x10^{-4}$	0.9487	982.72	145.2	10.87	1.694	1.764	4.9	4.3
R-NC-03-15	GT1	1.5998	1.6865	$7.205x10^{-4}$	0.9474	826.96	109.5	1.42	1.688	1.780	5.2	5.2
R-NC-03-16	GT1	1.5882	1.6724	$6.854x10^{-4}$	0.9485	853.08	111.13	5.69	1.674	1.763	6.0	4.2
R-NC-03-17	GT1	1.5748	1.6941	$6.730x10^{-4}$	0.9472	844.43	108.83	4.34	1.663	1.788	6.6	5.7
R-NC-03-18	GT1	1.6009	1.6387	$6.352x10^{-4}$	0.9473	874.65	119.14	4.43	1.690	1.730	4.7	3.6
R-NC-03-19	GT1	1.5682	1.7516	$7.716x10^{-4}$	0.9477	845.12	110.11	4.43	1.651	1.848	7.0	9.2
R-NC-03-20	GT1	1.5607	1.7557	$7.619x10^{-4}$	0.9511	921.00	119.87	15.63	1.641	1.846	7.8	8.3
R-NC-03-21	GT2	1.5795	1.6741	$6.980x10^{-4}$	0.9491	861.96	109.1	9.03	1.664	1.764	6.6	4.3
R-NC-03-22	GT2	1.5891	1.6760	$6.922x10^{-4}$	0.9495	863.21	108.40	10.61	1.674	1.765	6.0	4.3
Mean (μ)				$7.041 x10^{-4}$					1.6667	1.782		
Standard deviation (σ)				$1.442 x10^{-9}$					0.0225	0.0375		

* From the manufacturer data sheet: L_{AD} = 1.781 p.u., L_{AQ} = 1.692 p.u., while r_F is unavailable.

Three parameters were estimated from each data set: L_{AD}, L_{AQ}, and r_F. The operating point of the generator for each data set is shown, as well as the field current. The saturation factor for the direct axis is calculated and shown in the table for each case study. It is assumed that the saturation factor is the same in both the direct and quadrature axes.

It is necessary to apply the saturation factor to the estimated saturated inductances in order to obtain the unsaturated inductances. This will allow comparison to the manufacturer data and enable the assessment of the estimation method. Table 8.7 depicts the estimated unsaturated mutual inductances and their deviation from the manufacturer supplied mutual inductances. It should be noted that the manufacturer inductances L_{AD} and L_{AQ} are 1.781 p.u. and 1.692 p.u. respectively.

It is of practical interest to examine the change of the two mutual inductances with excitation, using both the estimated saturated values as well as the values corrected for saturation to obtain the unsaturated values. Fig. 8.2 shows the change in the estimated direct axis mutual inductance L_{AD} with the field current. A linear regression model is fitted to observe the trend in the estimated inductance over increasing saturation levels. As expected, there is a decrease in the apparent value of the inductance as the generator is driven to higher operating points.

Fig. 8.3 compares both the saturated and the unsaturated values of L_{AD} for all case studies. The stacked column graph shows the estimated parameters and the correction for saturation. An overall agreement between the unsaturated values is observed. The

unsaturated values of L_{AD} have a mean of 1.6667 p.u. and a standard deviation of 0.0225 p.u. All of the values of the unsaturated inductance L_{AD} agree to one decimal place.

The results of each case study for the quadrature axis mutual inductance L_{AQ} are summarized in Figs 8.4 and 8.5. The estimated values of the quadrature axis mutual inductance at different operating points are shown in Fig. 8.4. The trend in the saturated value of the inductance is decreasing, although the decrease is not as evident as in the case of L_{AD}. It should be noted that the variation of L_{AQ} is slightly higher than that of L_{AD} since the standard deviation among the unsaturated parameters is 0.0375 p.u. The mean of the unsaturated parameters is 1.782. A comparison between the unsaturated values of L_{AQ} at each operating point is offered in Fig. 8.5, where the saturated inductances are corrected for saturation using the appropriate saturation factor at each operating point. With the exception of two data sets, the unsaturated values of the inductance agree to one decimal place.

Appendix F presents parameter estimation results for two steam turbine generators located at the Redhawk generating station of APS. A number of case studies are performed and an analysis similar to the analysis of this section is offered.
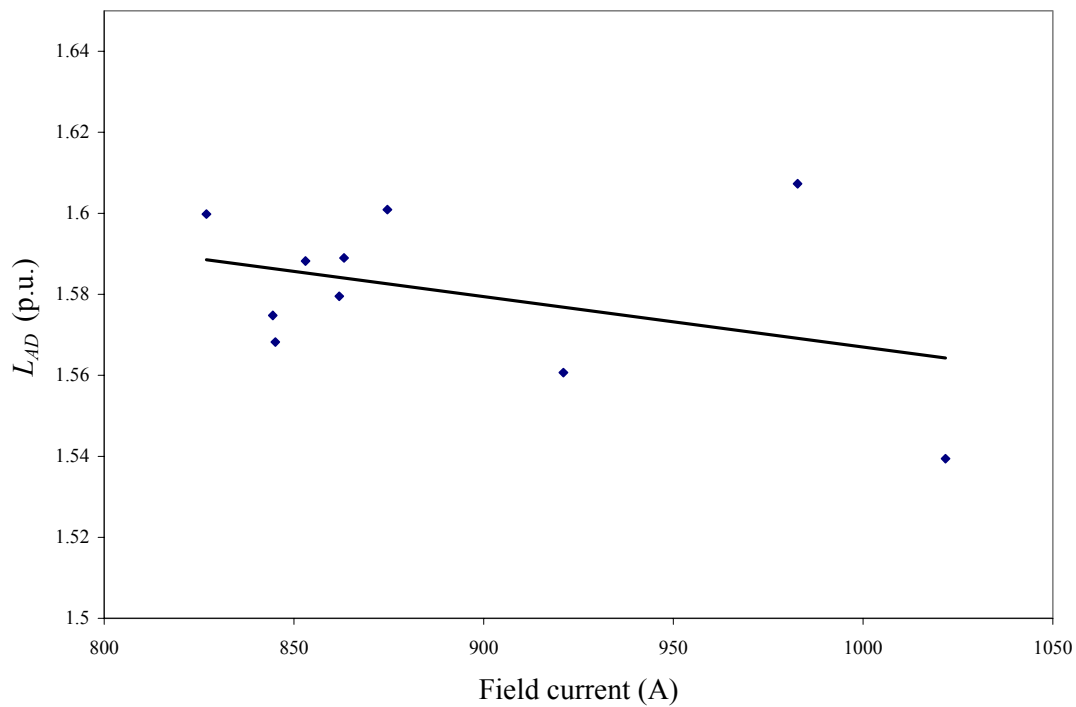
Fig. 8.2. Change of L_{AD} with operating point for Redhawk gas turbine generators
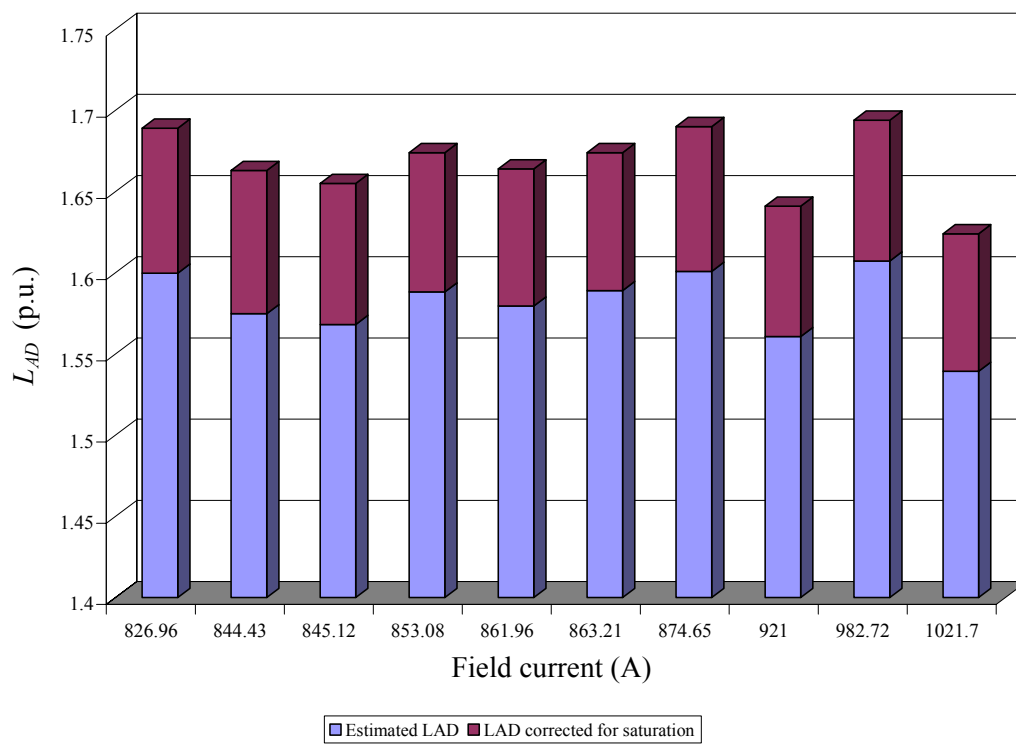
Fig. 8.3. Saturated and unsaturated values of L_{AD} for Redhawk gas turbine generators
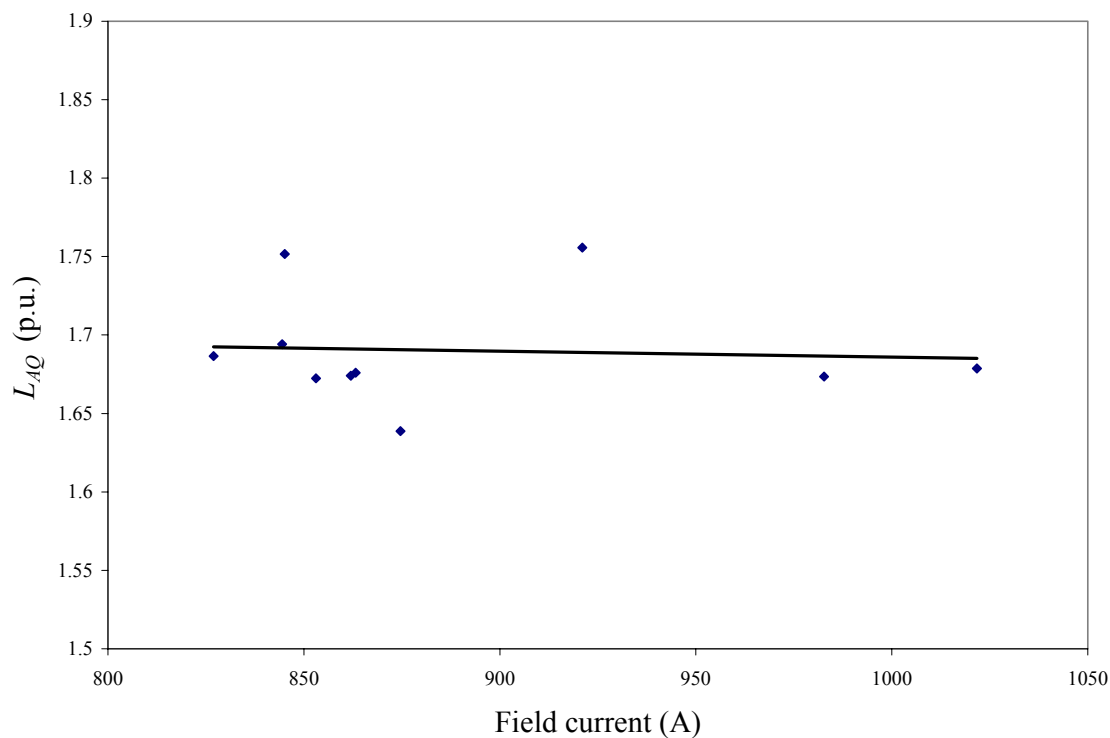
Fig. 8.4. Change of L_{AQ} with operating point for Redhawk gas turbine generators
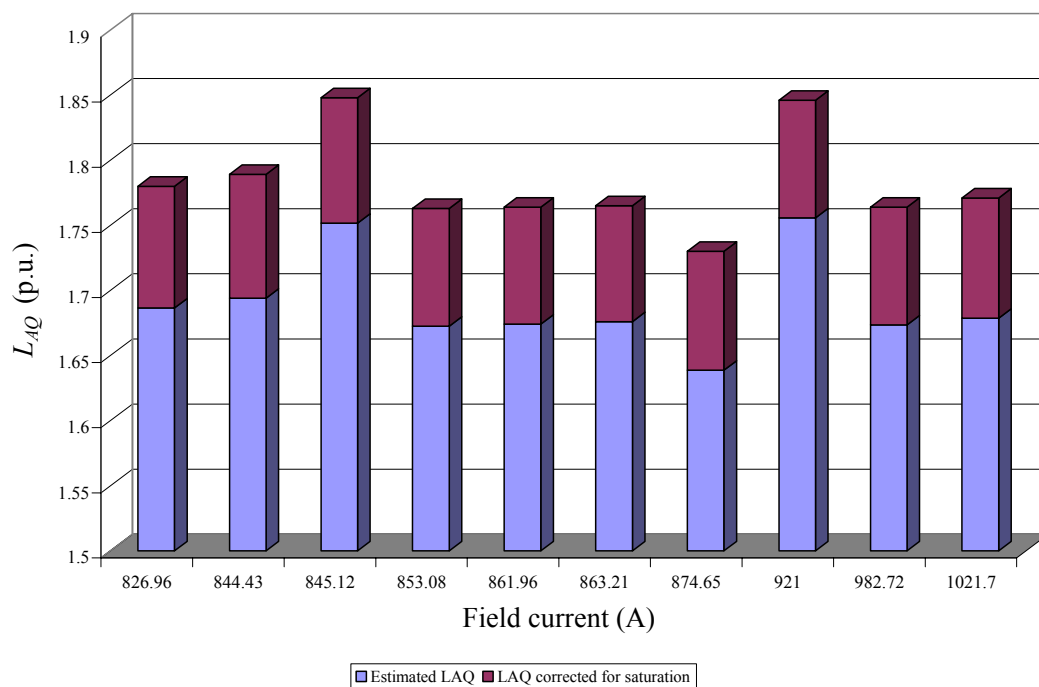
Fig. 8.5. Saturated and unsaturated values of L_{AQ} for Redhawk gas turbine generators

8.5 Calculation of standard machine parameters from estimated derived parameters

Typically machine parameters obtained from manufacturer data are as shown in the stability study data sheet in Appendix B.2. These machine parameters are referred to as standard machine parameters and include the direct and quadrature axis reactances and their transient and subtransient counterparts, as well as the transient and subtransient time constants. However, the estimated parameters obtained through the model developed in Chapters 2 and 3 are derived parameters from these standard machine parameters.

Therefore, it is necessary to calculate the standard parameters from the estimated parameters obtained through the developed algorithm. Table 8.8 summarizes the formulae that are needed to perform the conversion from derived parameters to standard parameters. Table 8.9 compares estimated standard parameters to manufacturer standard parameters for case study R-NC-01-10 (generator FC5HP).

The results of Table 8.9 show a good correlation between the estimated standard parameters and the manufacturer standard parameters. The correction for saturation typically improves the estimates. Some of the parameters such as the transient and subtransient inductances are estimated with errors less than 0.3%. The highest error is observed for the direct axis transient open circuit time constant and it is equal to 5.5%.

TABLE 8.8

Calculation of standard parameters from the estimated derived parameters*

Parameter name	Parameter symbol	Formula
Equivalent direct axis reactance	x_d	$L_{AD} + \ell_d$
Transient direct axis reactance	x_d'	$\dfrac{\ell_F L_d + L_{AD}\ell_d}{L_{AD} + \ell_F}$
Subtransient direct axis reactance	x_d''	$\ell_d + \dfrac{1}{\dfrac{1}{L_{AD}} + \dfrac{1}{\ell_D} + \dfrac{1}{\ell_F}}$
Equivalent quadrature axis reactance	x_q	$L_{AQ} + \ell_q$
Transient quadrature axis reactance	x_q'	$\dfrac{\ell_G L_q + L_{AQ}\ell_q}{L_{AQ} + \ell_G}$
Subtransient quadrature axis reactance	x_q''	$\ell_q + \dfrac{1}{\dfrac{1}{L_{AQ}} + \dfrac{1}{\ell_G} + \dfrac{1}{\ell_Q}}$
Direct axis transient open circuit time constant	τ_{d0}'	$\dfrac{L_{AD} + \ell_F}{\omega_B r_F}$
Direct axis subtransient open circuit time constant	τ_{d0}''	$\dfrac{1}{\omega_B r_D}[\ell_D + \dfrac{1}{\dfrac{1}{L_{AD}} + \dfrac{1}{\ell_F}}]$
Quadrature axis transient open circuit time constant	τ_{q0}'	$\dfrac{L_{AQ} + \ell_G}{\omega_B r_G}$
Quadrature axis subtransient open circuit time constant	τ_{q0}''	$\dfrac{1}{\omega_B r_Q}[\ell_Q + \dfrac{1}{\dfrac{1}{L_{AQ}} + \dfrac{1}{\ell_G}}]$

*Note: Time constants are in seconds. All other quantities are in per unit.

TABLE 8.9

Comparison of estimated standard parameters to manufacturer standard parameters

(case study R-NC-01-10)*

Parameter	Manufacturer value	Value at operating point	Unsaturated value	% Deviation
x_d	1.80	1.7563	1.897	5.4
x_d'	0.27	0.2698	0.2704	0.15
x_d''	0.19	0.18998	0.19003	0.02
x_q	1.72	1.5657	1.6894	1.78
x_q'	0.49	0.48251	0.48861	0.28
x_q''	0.19	0.18994	0.18999	0.005
τ_{d0}'	3.70	3.60802	3.90376	5.5
τ_{d0}''	0.032	0.03196	0.03209	0.28
τ_{q0}'	0.49	0.45179	0.48243	1.54
τ_{q0}''	0.059	0.05778	0.05877	0.39

*Note: Time constants are in seconds. All other quantities are in per unit.

CHAPTER 9

GRAPHIC USER INTERFACE IMPLEMENTATION USING VISUAL C++

9.1 Introduction

One of the major objectives of this research work is to develop a visual graphic user interface (GUI) in the form of a Windows application for a synchronous generator state estimator. This application will enable the practicing engineer and interested utilities to estimate the parameters of a synchronous generator without having to decommit the unit or get involved in time consuming off-line tests. The application developed during this research work is unique due to three main characteristics: on-line operation, portability, and user friendly interaction.

On-line operation is the distinguishing characteristic of the proposed estimator. It enables on-line and expeditious estimation of any given synchronous generator based on measurements of the field and stator voltages and currents. Such measurements are readily available and in large quantities in every utility.

Moreover, the application developed is portable, since it can be installed in any personal computer operating under Windows. It does not require a Visual C++ environment, since it is a stand-alone application, able to operate without the support of external C++ libraries.

Finally, user friendly interaction is achieved by means of the dialogs and context-sensitive help provided on request. The input and output dialogs are self explanatory and will be analyzed in Sections 9.2 and 9.4 respectively. Moreover, these dialogs and each of their components are analyzed within the program itself in the Help section.   General

guidelines for correct operation of the program and interpretation of the results are also provided.

9.2 Input dialog and estimator configuration

The main window of the estimator offers a variety of options on its toolbar, similar to any other Windows program. To initiate the process of estimating generator parameters, the user must open the input screen as shown in Fig. 9.1. This is achieved by selecting the option *Estimator* on the toolbar of the main window, and then selecting the *Set up Estimator* option.

Fig. 9.1. Input window of the *Estimator*

As can be seen in Fig. 9.1, the input screen is user friendly. The user can set up the *Estimator* and calculate the parameters of the synchronous generator that is to be

studied by following the directions on the input screen. The first step is to enter the name of the data file in the edit box as shown in Fig. 9.1. This can be done by clicking on the *Browse* button and navigating through the hard disk of the computer or any external drives until the desired file is located. The file can be of any data format type (for example .dat or .txt). If applicable, the user can select the IEEE COMTRADE option by clicking on the respective radio button and the *Estimator* will read the measurements as obtained directly from the measuring device that is connected to the generator. These files typically follow the IEEE COMTRADE Standard for power systems [116]. An example of each data format that is supported by the application can be seen in Appendix E.

The second step on behalf of the user is to input the required parameters as contained in the manufacturer data sheet of the synchronous generator (see Appendix B for a sample manufacturer data sheet). Sample values are shown in Fig. 9.1 and these are the values obtained from the generator manufacturer data of Appendix B.

The user is able to select various options pertaining to the estimation process. It is possible to perform either a least squares estimation (L_2 minimization) or a minimization of absolute deviations using the L_1 norm [77]. In this research work, the estimation was performed in a least squares sense.

Further, the user may select the level of filtering that is desired. Of the two options, the full filtering is preferred since it will minimize the noise content in the measured signals. Finally, the user is given the option to apply weights to the measurements. This is particularly useful if it is known that certain measurements are

less reliable than other measurements. Further documentation on all the options is provided through context-sensitive help or through the buttons that are located on the input window. Fig. 9.2 shows a view of the *Help* window developed for the *Estimator*.

The final step of this process is to select the parameters that need to be estimated. The user has the opportunity to select up to five parameters for estimation. This selection can be performed by simply clicking on the check box corresponding to the parameter to be estimated, as shown in Fig. 9.1.
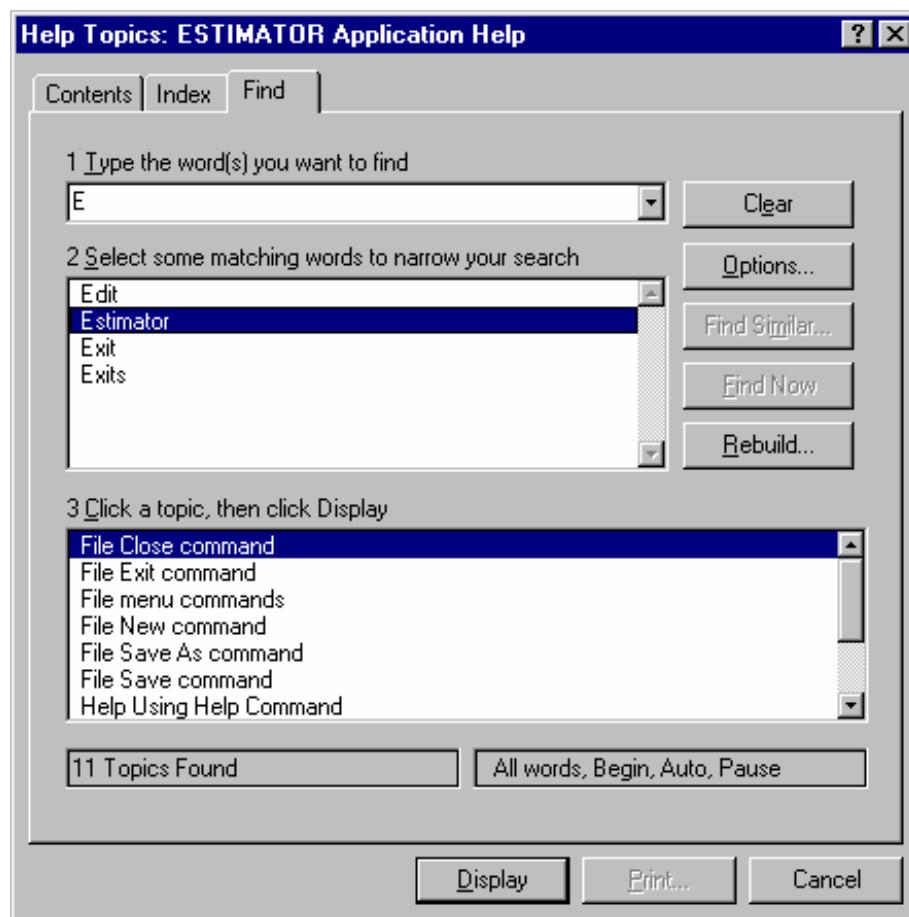
Fig. 9.2. View of the *Help* window of the *Estimator*

9.3 State estimator implementation

After completing the steps mentioned in the previous section, the user clicks the *Start Estimator* button to enable estimation of the parameters. No other interaction is required from the user. The *Estimator* is responsible to read the data from the input file, perform the bad data detection and rejection algorithms, filter the noise from the measurements, and calculate the current derivatives. It implements the state estimation algorithm and returns the values of the estimated parameters as an output. The C++ code for the non GUI part of the application can be seen in Appendix H. The *Estimator* flowchart can be seen in Fig. 9.3.

9.4 Output dialog and estimated parameters

Upon execution of the main program of the application the values of the estimated parameters, the rms error, and the confidence level in the estimated parameters are returned to the graphic user interface for output. The resulting output window can be seen in Fig. 9.4. On the left side of the output window, the user can see the parameters that he/she previously selected and their estimated value in per unit. The rms error on the lower right side of the estimator is a measure of confidence on the estimated parameters and is given by,

$$rms\ error = \sqrt{residual \Big/ number\ of\ measurements} \ , \qquad (9.1)$$

where,

$$(residual)^2 = (H\hat{x} - z)^T (H\hat{x} - z), \qquad (9.2)$$

and $\hat{x}$ is the vector of the estimated parameters.
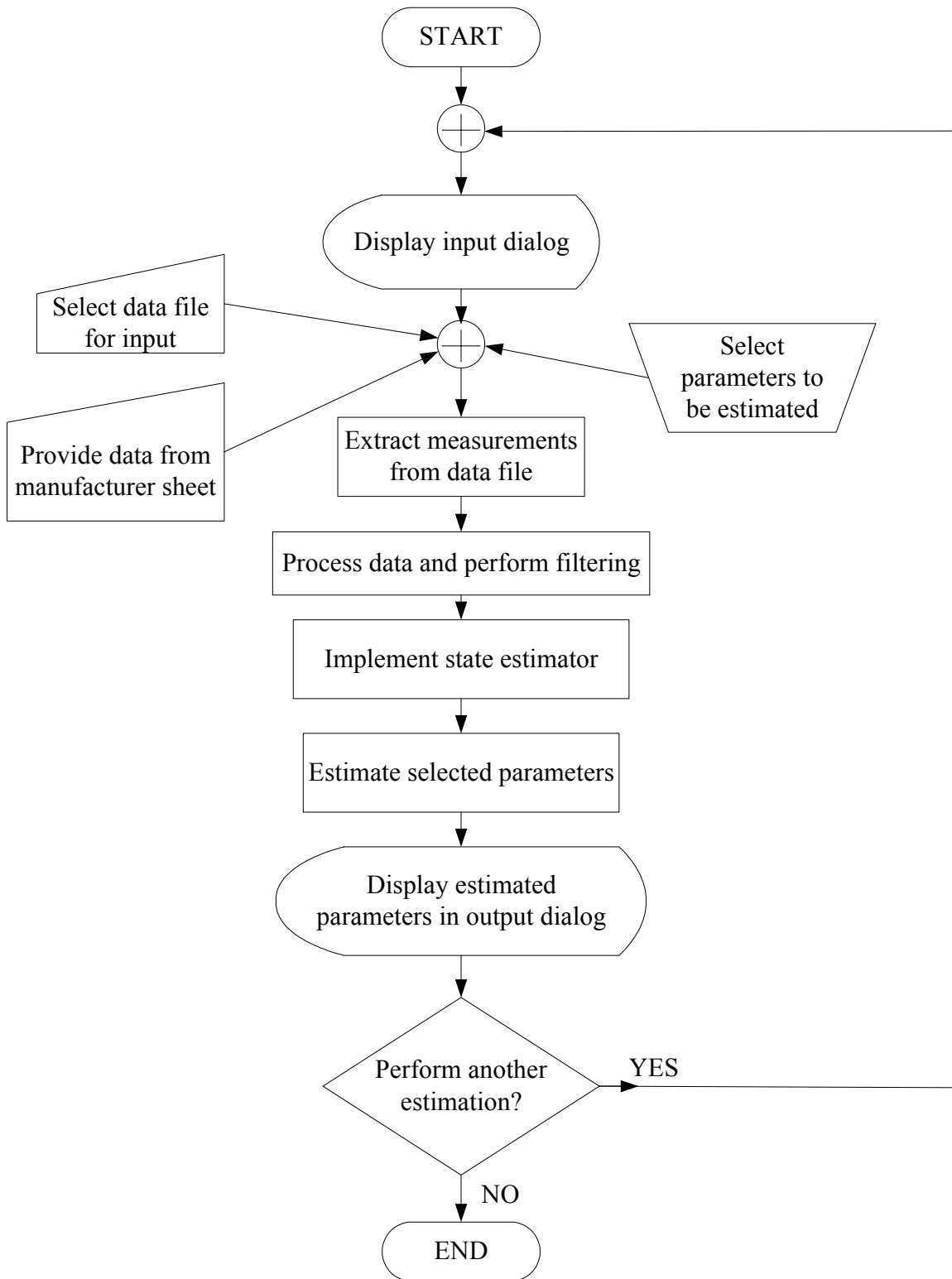
Fig. 9.3. Flowchart for GUI and estimator implementation

```
Estimated data                                                        ☒

  ┌─ Estimation results ──────────────────────┐   ┌──────────────────┐
  │                                           │   │        OK        │
  │  PARAMETER   ESTIMATED VALUE (p.u)         │   └──────────────────┘
  │  ┌──────┐    ┌──────────────┐              │   ┌──────────────────┐
  │  │ r    │    │ 0.0042235    │              │   │ Another Estimation│
  │  └──────┘    └──────────────┘              │   └──────────────────┘
  │  ┌──────┐    ┌──────────────┐              │   ┌──────────────────┐
  │  │ Lq   │    │ 1.5300312    │              │   │Interpretation of results│
  │  └──────┘    └──────────────┘              │   └──────────────────┘
  │  ┌──────┐    ┌──────────────┐              │   ┌──────────────────┐
  │  │ Ld   │    │ 1.5997191    │              │   │ View history file │
  │  └──────┘    └──────────────┘              │   └──────────────────┘
  │  ┌──────┐    ┌──────────────┐              │
  │  │ rF   │    │ 0.0008999    │              │
  │  └──────┘    └──────────────┘              │
  │  ┌──────┐    ┌──────────────┐              │
  │  │ LF   │    │ 1.5608084    │              │
  │  └──────┘    └──────────────┘              │   ┌─ Confidence index ──────┐
  │                                           │   │ RMS Error:  │ 0.129743 │ │
  │                                           │   │ Confidence level: HIGH  │ │
  │                                           │   └─────────────────────────┘ │
```
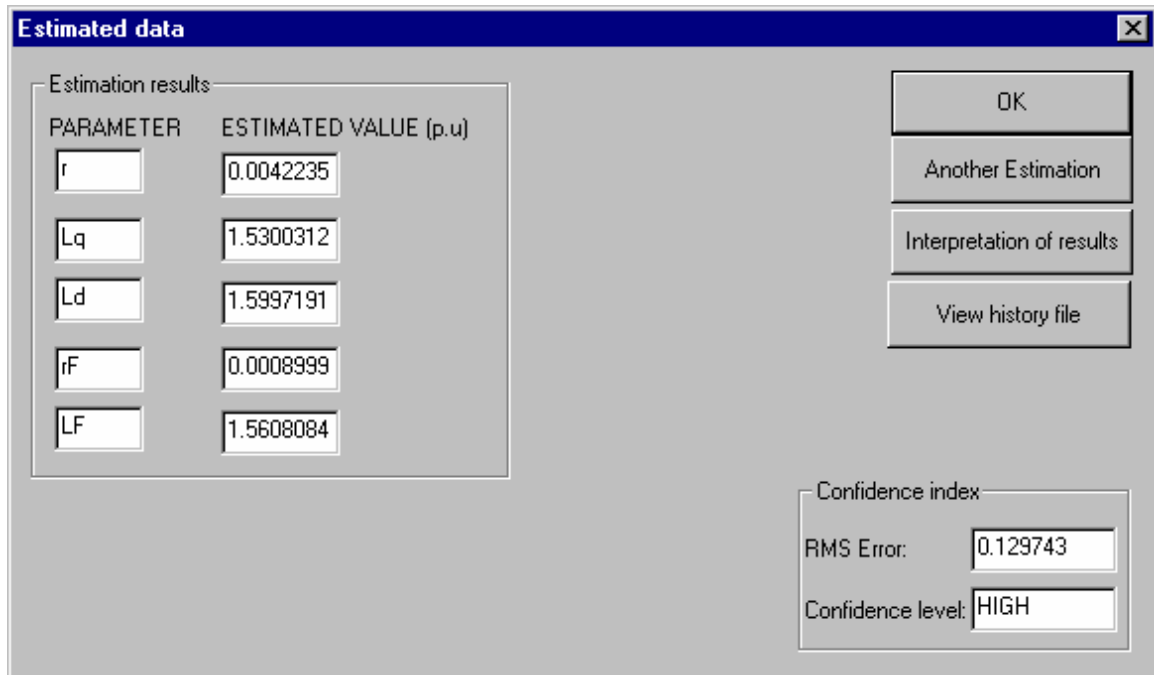
Fig. 9.4. Output window of the *Estimator*

Finally, a confidence level is offered to the user. The confidence level has three states: high, average, or low. In this fashion, the user can verify whether the measurements used are reliable or not. Section 9.5 discusses how such a confidence level can be derived through the χ^2 test, and Section 9.6 proposes a method to calculate a confidence interval for the estimated parameters.

9.5 Interpretation of the rms error and the chi-squared test

Small values of rms error as calculated by the *Estimator* in Fig. 9.4, indicate high reliability of results. Larger values of rms error indicate results that cannot be trusted for correct interpretation. The residual, which is the basis for the calculation of the rms error, is ideally equal to zero for error free estimations. Its value represents a measure of how

closely the estimated values follow the measured or expected values. Instead of relying on intuition as to how large or how small the residual or the rms error should be, a standardized method could be followed to ascertain reliability of the results. A widely used method for such purposes is the χ^2 test. This method will be analyzed in this section.

The residual $J(x)$ is a random number since the measurement errors are random numbers as well. Therefore, it can be shown that $J(x)$ has a probability density function known as a chi-squared distribution, also written as $\chi^2(K)$. K is called the degrees of freedom of the chi-squared distribution and is defined as,

$$K = N_m - N_s,$$
(9.3)

where N_m is the number of measurements, and N_s is the number of states. The mean value of the chi-squared distributed residual is K, and its standard deviation is $\sqrt{2K}$ [50].

To ascertain how large a residual needs to be so as to be considered as a bad estimation, the χ^2 test has to be set up. A threshold value of $J(x)$ has to be decided and this value is denoted t_J. Such threshold values can be in the order of three times the standard deviation as noted above. Therefore, if $J(x) > t_J$, then bad measurements or unreliable estimation is detected. The next step is to calculate the probability that $J(x) > t_J$. This probability is called the significance level α and it is desired to be as small as possible.

An alternative way but similar to the above procedure, is to set the significance level first and then calculate the threshold value. This can allow indication of the probability of the occurrence of false alarms, which is equal to α. For example, by setting

α to 0.01, the probability of receiving a false alarm for unreliable estimation is 1%. Knowing the value of α, the threshold value t_J can be calculated and compared to the residual $J(x)$. If t_J is greater that $J(x)$, then the estimated results are reliable. Fig. 9.5 graphically shows the chi-squared test and how to determine reliability of the results as explained in this section. Tables for threshold values at various degrees of freedom and various significance levels are available in the literature [117].
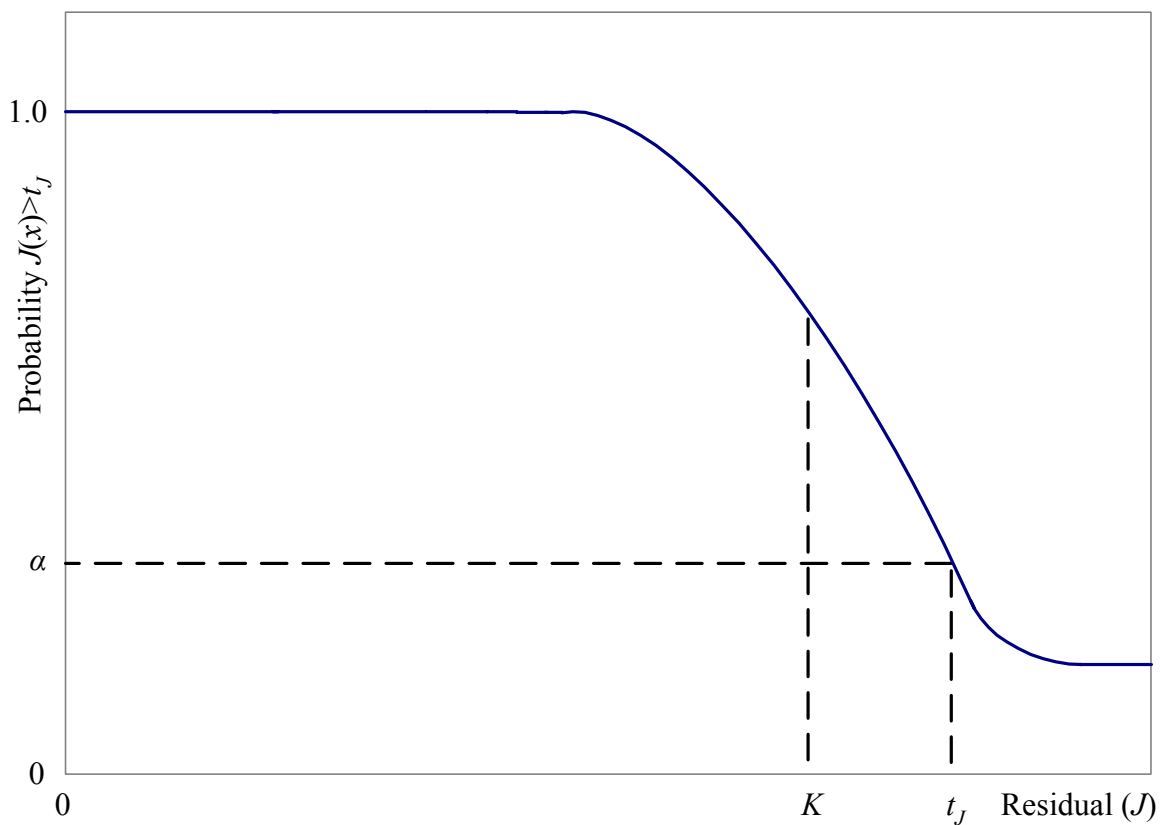
Fig. 9.5. Chi-squared test probability function

9.6 Confidence interval for estimated parameters

The estimated parameters always contain a certain level of inaccuracy because of the finite amount of noise in the measurements. Using improved filtering methods or an increased number of measurements may reduce the inaccuracy, but the values obtained can never be exact. It is therefore advantageous to be able to specify a confidence interval for each estimated parameter based on the instrumentation used to obtain measurements, on the number of measurements used, and on the particular configuration of the system model.

The final form of the equation of the model is given by $Hx = z$, where H is an $m \times n$ matrix containing the coefficients of the parameters to be estimated, x is an $n \times 1$ vector that is desired to be estimated, and z is an $m \times 1$ vector that contains both known parameters and measurements. Clearly, both H and z contain a certain level of measurement uncertainty (in the form of noise). H contains measurement noise in all its nonzero entries, whereas z contains measurement noise in all of its entries since its entries are a sum of products between known values of parameters and their measured coefficients.

Most instrumentation devices offer an accuracy of measurement for each scale that is used. For example, if a meter on a transmission line has a scale of 100 MW and an accuracy of ± 2 MW, then this can be associated to a percentage confidence of any measurement. (The usual practice is to associate the accuracy to a value equal to three times the standard deviation of the normal probability function of the distribution of the error [50], but here a different formulation is proposed). Therefore, if a measurement of

100 MW is obtained by the instrument, the user can assume that the actual value of the measured power is between 98 and 102 MW. Similarly, if the indication of the instrument is Y MW, then the user can assume that the actual measurement is between $Y + Y \frac{2}{100}$ and $Y - Y \frac{2}{100}$. In general, if an instrument has a full scale denoted as F_S, an accuracy σ, and a measured indication Y, then the actual measurement $\overline{Y}$ can be assumed to be between,

$$Y - Y \frac{\sigma}{F_S} \leq \overline{Y} \leq Y + Y \frac{\sigma}{F_S} . \tag{9.4}$$

All measurements in H and z of $Hx = z$ can therefore be expressed in terms of the meter accuracy similarly to (9.4), and the model equation can be rearranged as

$$(H + \Delta H)x = (z + \Delta z), \tag{9.5}$$

where ΔH and Δz contain the adjustment for the inaccurate terms. The solution of the system can thus be obtained by,

$$\hat{x} = (H + \Delta H)^+ (z + \Delta z) \tag{9.6}$$

In order to find a confidence interval for the estimated solution, it is necessary to estimate the possible maximum deviation $\Delta \hat{x}$ from the solution $\hat{x}$. A least squares solution for $Hx = z$ satisfies the normal equations,

$$H^T Hx = H^T z . \tag{9.7}$$

Similarly, a least squares solution for (9.5) satisfies the normal equations,

$$(H + \Delta H)^T [(H + \Delta H)(x + \Delta x) - (z + \Delta z)] = 0 . \tag{9.8}$$

It should be noted that in this application, rank(H) = rank($H+\Delta H$) = n. The full column rank in H is due to the fact that the entries in matrix H are the coefficients of the unknown parameters; all of these coefficients are nonzero (n is the number of the parameters to be estimated).   Further, $H+\Delta H$ has a full column rank since noise components appear in the same locations in ΔH as do in H (noise only appears in measurements, all other elements are zero). If H does not have a full column rank, then the upper bound of the matrix pseudoinverse does not necessarily tend to zero as the perturbation tends to zero.

Subtracting the noise free solution (9.7) from (9.8) and expanding without neglecting any second order terms, the deviation from the true solution can be obtained as,

$$\Delta \hat{x} = [(H + \Delta H)^T (H + \Delta H)]^+ \Delta H^T (z - Hx) + (H + \Delta H)^+ (\Delta z - \Delta Hx). \qquad (9.9)$$

Although (9.9) is an "exact" mean square solution for the deviation $\Delta \hat{x}$, the main disadvantage of this approach is that it is necessary to know x: the noise free, mean square solution of the linearized system $Hx = z$. However, if x were known, then it would not be necessary to attempt to estimate $\Delta \hat{x}$. Therefore, an alternative approach needs to be followed to obtain an approximate equation that does not involve knowledge of the true mean square solution. The alternative approach proposed in the remainder of this section involves the approximation of the pseudoinverse of $(H + \Delta H)$.   This approximation will enable the expansion of (9.6), and an easier method of isolating $\Delta \hat{x}$.

First, consider the scalar case. Suppose that it is desired to find an approximate equation for the inverse of the quantity $(h + \delta h)$. This quantity can be rewritten as,

$$(h + \delta h)^{-1} = h^{-1}(1 + h^{-1}\delta h)^{-1}. \tag{9.10}$$

Using Taylor series expansion and expanding up to the third term,

$$(h + \delta h)^{-1} = h^{-1}(1 - h^{-1}\delta h + (h^{-1}\delta h)^2 - \cdots). \tag{9.11}$$

Equation (9.11) may be used to relate the scalar case to the matrix case. The pseudoinverse of $(H + \Delta H)$ can be written as,

$$(H + \Delta H)^+ \approx H^+ - H^+ \Delta H H^+ + H^+ (\Delta H H^+)(\Delta H H^+). \tag{9.12}$$

Substituting (9.12) into (9.6), an expression in terms of $\hat{x}$ and $\Delta\hat{x}$ can be obtained.

$$\begin{aligned}
\hat{x} &= (H + \Delta H)^+ (z + \Delta z) \\
&\approx [H^+ - H^+ \Delta H H^+ + H^+ (\Delta H H^+)(\Delta H H^+)](z + \Delta z) \\
&\approx H^+ z + [H^+ (\Delta H H^+)(\Delta H H^+) - H^+ \Delta H H^+]z \\
&\quad + [H^+ - H^+ \Delta H H^+ + H^+ (\Delta H H^+)(\Delta H H^+)]\Delta z.
\end{aligned} \tag{9.13}$$

The first term of (9.13) is recognized as the solution to the noise free system $Hx = z$ and therefore the remainder of (9.13) can be called the deviation $\Delta\hat{x}$ from the true solution. Rearranging (9.13),

$$\Delta\hat{x} \approx H^+ \Delta H H^+ (\Delta H H^+ - I_{mxm})z + H^+ (I_{mxm} - \Delta H H^+ + (\Delta H H^+)(\Delta H H^+)]\Delta z, \tag{9.14}$$

where H and z are known, and ΔH and Δz can be estimated as explained in the beginning of the section. The confidence interval can thus be calculated as,

$$\hat{x} - \Delta\hat{x} \leq \bar{\hat{x}} \leq \hat{x} + \Delta\hat{x}. \tag{9.15}$$

CHAPTER 10

CONCLUSIONS AND FUTURE STEPS

10.1 Comments from industry

The research work performed in this dissertation attempts to solve a well defined industry problem namely the identification of synchronous generator parameters at various operating levels and the tracking of parameters over time to potentially prevent system outages. A number of utilities and private companies have expressed an interest in this research work and the graphic user interface that is being developed. A number of industry members is involved directly or indirectly in this work and at times offered suggestions, comments, and constructive criticism about the development of the estimator.

All the issues raised by the industry are of practical manner. Some of the major issues include the unavailability of damper winding current measurements and the implementation of a saturation model for synchronous generator inductances. Some other issues that have been discussed are the differences in the configuration of the exciter in synchronous generators, the extension of this research work to other generators, and the improvement of the confidence in the results by using measurements from various generators. Table 10.1 summarizes some of the comments and concerns received by industry members during private discussions or during various presentations of this research work at international conferences.

TABLE 10.1

Comments from the power engineering industry

Area	Industry comment	Plan of action
Exciter	Is the estimator applicable to brushless exciter applications?	The estimator requires voltage and current measurements from the field winding. It is necessary for the exciter to have brushes in order to be able to obtain these measurements. However, it may be possible to develop an observer for the field voltage and current. This subject is under investigation.
Damper windings	The damper windings cannot be measured. How does the estimator obtain these measurements?	Chapter 4 describes an observer for damper winding currents. Results from simulated data verify its operation.
Magnetic saturation	Can magnetic saturation be implemented in the estimator?	A model for magnetic saturation is currently used as shown in Chapter 3. A model to estimate the q axis characteristic from the d axis characteristic has been developed by a number of researchers and is also presented in Chapter 3.
Superconducting synchronous condensers	Can the estimator be applied to a superconducting synchronous condenser?	The idea proposed in this research work can be applied to any generator that can be described by a model similar to the one of a round rotor synchronous generator.
Further experience	Is it possible to obtain further experience with the estimator using data from other generators?	A number of synchronous generator data have been obtained from APS. These data pertain to six different generators (both steam and gas turbines). Some of the results are shown and analyzed in Chapter 8 and Appendix F.

10.2 Conclusions

In this dissertation, a method to identify synchronous generator parameters from on-line measurements is presented. Knowledge of parameter values at different operating levels enables the correct representation of synchronous generators in stability studies and other routine power engineering studies. Proper representation of synchronous generators leads to increased accuracy in the results obtained from these studies as well as better operation and maintenance of the power system network. Additionally, the ability to foresee turn to turn short circuits in the generator field winding potentially enables the engineers to avoid forced outages, thus saving the company huge amounts of money in downtime, rewinding of the generator, and lost dividends from the operation of the generator.

The method proposed in this report is based on least squares estimation of a system of equations based on measurements obtained while the generator is connected to the power system and serves its load. The on-line collection of measurements makes the method superior to off-line methods since it is possible to estimate generator parameters at various operating levels. The developed model of the system was shown to contain seven differential equations that represent the stator and the rotor of the generator as well as three damper windings.

One of the most important obstacles in the parameter estimation algorithm is the unavailability of damper winding currents. Currently there is no proven technology for the direct measurement of damper winding currents using physical instruments. Moreover, damper windings are often fictitious and they are an effect of eddy currents in

the rotor path. Therefore it is necessary to estimate damper winding currents. An observer for the estimation of damper currents that is based on the model of the system and *a priori* knowledge about the system was proposed in this dissertation and implemented in the parameter estimation algorithm. Comparison to both steady state and transient simulated measurements showed that the damper currents were estimated accurately.

Magnetic saturation affects some of the generator inductances significantly. In order to enable estimation of parameters at various operating levels, it is imperative to model saturation effectively so that the estimated parameters reflect the true state of the system. A saturation model was implemented in this dissertation based on knowledge of the saturation curve of the direct axis. A saturation factor that was calculated from the saturation model was used to modify the values of inductances that were used in the estimation process. Parameter estimation results show that magnetic saturation is represented effectively. A possible improvement of the saturation representation is to calculate separate saturation factors for the direct and quadrature axes. Because of the unavailability of q axis saturation data, it is necessary to approximate the q axis saturation characteristic. A method to estimate the q axis open circuit characteristic from the available d axis open circuit characteristic is shown in Chapter 3.

Noise suppression is of major concern in this research work. Actual generator data always contain noise that needs to be reduced in order to improve the accuracy of the estimated parameters. Several types of digital filters have been considered in order to filter out high frequency noise in the stator and rotor measurements. The Butterworth

filter is selected to be implemented because of its desirable characteristics in the passband, and especially because of the small amount of ripple in its response. A multiple parallel filtering method was proposed to implement noise filtering in an effective manner because of the spread of the frequency spectrum of the signals. Multiple parallel filtering in effect applies the same filter a number of times to slowly attenuate all frequency components that are located in the transition band of a signal. For "noise" that is actually harmonics, in either the field or armature, a small possible improvement might be obtained by modeling the effects of these harmonics rather than simply discarding the harmonic portion of the spectrum.

Three synchronous generator models have been proposed in this dissertation. Model 2.2x seems to be the dominant model because of its more accurate modeling of the quadrature axis, the easier implementation of saturation, and the favorable results obtained from synthetic data and actual measurements.

The synchronous generator models and the proposed method were verified using synthetic data obtained from the solution of the differential equations of the model and from the simulation of the generator in EMTP. The latter method allowed the estimation of generator parameters with a maximum error of 0.39%, while the stator resistance and the field resistance were estimated exactly.

The proposed method was subsequently tested using on-line measurements from synchronous generators. In case study R-NC-01-10, the field resistance was estimated with a deviation of 0.8% for all three proposed models for generator FC5HP. The direct axis inductance L_d was estimated with a deviation of 2.4% for both models 2.1 and 2.2,

while the quadrature axis inductance L_q was estimated with a deviation of 1.0% for model 2.1 and 0.2% for model 2.2 respectively. In the case of model 2.2x, the direct axis mutual inductance L_{AD} was estimated with a deviation of 5.9%, while the quadrature axis mutual inductance L_{AQ} was estimated with a deviation of 2.0%. It is possible that the deviation of the estimated parameters from the manufacturer supplied parameters is due to inaccurate modeling of saturation, change of generator parameters over time, and the fact that the rotor of the generator under study has been rewound at least three times during its operating history. Therefore it is possible that the manufacturer supplied parameters do not reflect the present state of the generator.

In this dissertation it was demonstrated that multiple parameter estimation is feasible. A number of case studies performed using both synthetic and actual measurements illustrated that the accuracy of the estimation does not degrade as the number of parameters increases. This enables the estimation of more than one parameter at a time and it is a particularly useful result since there is often uncertainty in more than one generator parameter.

In order to ascertain the validity and the accuracy of the proposed algorithm for other synchronous generators, and to examine whether it is possible to estimate parameters at different operating points, a number of case studies were performed. Data sets from gas turbines GT1 and GT2, as well as from steam turbines ST1 and ST2 indicated a consistency in the estimated parameters over a range of operating points. A decreasing trend in the value of the mutual inductances was observed as the generators were driven deeper into the saturation region. This is consistent with magnetic saturation

theory, since the apparent value of the inductance is expected to decrease as the magnetic field intensity increases beyond the saturation threshold of the magnetic material. Further, the estimated unsaturated inductances at all operating points had small deviations from the mean for all generators under study. This shows a consistency in the representation of saturation at all operating levels. It should also be noted that for the steam turbine units the stator resistance was unavailable. Nevertheless, consistent estimates were obtained.

Table 10.2 presents possible sources of deviation from manufacturer supplied parameters. These deviations may be due to inaccuracies in the estimated parameters and the modeling of the generator, or due to inaccuracies in the manufacturer supplied parameters.

The method presented in this dissertation is developed to be used with a Visual C++ engine and graphic user interface (GUI), so that the practicing power engineer may link synchronous generator measurements taken in an on-line environment with the *Estimator*. The GUI application is user friendly and self guiding so as to enable prompt estimation of the desired parameters. The required data that are needed to perform the estimation process can be read off the manufacturer data sheet for the generator under study, and can be supplied to the input screen of the *Estimator*. The data file and the desired parameters that need to be estimated can also be selected on the input screen. The estimated parameters are then displayed on the output screen.

TABLE 10.2

Principal sources of differences between estimated and manufacturer parameters

Type of deviation	Source of deviation	Description of deviation
Inaccuracy in estimated parameters	Filtering	It may be possible that in some cases noise is not filtered completely, or that some frequency components of interest are filtered out.
Inaccuracy in estimated parameters	Harmonics	Harmonics in the measured signals were treated as noise. It may be possible that some of the harmonic components are not noise and that these components have an effect on the actual machine performance.
Inaccuracy in estimated parameters	Linear model	The model representing the synchronous generator is a linear model. However, physical systems are generally nonlinear. Representing a nonlinear model as linear introduces a degree of inaccuracy.
Inaccuracy in estimated parameters	Representation of magnetic saturation	Saturation is a highly nonlinear, complex phenomenon. To represent saturation a number of assumptions are made. Some of these assumptions have an impact on the accuracy of the estimates.
Inaccuracy in estimated parameters	Modeling	A synchronous generator is a complex system with many parameters. In order to develop a practical model of the system, assumptions need to be made as to whether certain components of the system deserve modeling. It is possible that some of the neglected components have an effect on the machine performance at certain operating levels.
Inaccuracy in estimated parameters	Measurements	Noise, incomplete metering, spikes, and A/D conversion error cause inaccuracies in the measurements. A filtering mechanism cannot extract perfect measurements from noisy measurements and therefore the estimated parameters will contain a certain amount of error.
Inaccuracy in manufacturer parameters	Manufacturer supplied parameters not accurate	Generators are manufactured based on design data. In some cases these design data are shown on the manufacturer stability data sheet. Therefore the actual parameters of each manufactured generator may differ from the design (desired) parameters.
Inaccuracy in manufacturer parameters	Manufacturer supplied parameters not accurate	It is possible that some of the parameters reported on the manufacturer stability data sheet are not measured directly but are calculated parameters. ANSI Standard C50.13-1977 indicates which tests should be performed on a generator, and which can be substituted by results obtained from tests on a duplicate generator. For example, transient and subtransient reactances are typically calculated, not measured.
Inaccuracy in manufacturer parameters	Machine repairs	Often machines undergo repairs (e.g. rewinding the field of the rotor). These repairs cause changes in the machine parameters. Sometimes the changes are significant.
Inaccuracy in manufacturer parameters	Differences in operating point and operating conditions	The machine parameters reported in the manufacturer data sheets are measured at specific operating conditions and a certain level of excitation and temperature. The operating conditions of the machine in the estimation interval are probably different. Further, aging causes changes in the physical properties of the machine parts; these changes are reflected in the machine parameters.

10.3 Future steps

The results obtained from the proposed method and their subsequent analysis in this report demonstrate that the parameter identification algorithm proposed is potentially an accurate method for the estimation of generator parameters. Therefore, future steps need to be directed towards the enhancement of the accuracy of the results and the utilization of the acquired knowledge for the improvement of certain features of the algorithm.

One of the most important issues that deserve attention is the modeling of magnetic saturation. A saturation model was proposed and implemented in this research work. Because of the unavailability of q axis saturation data, the saturation in the two axes of the generator was assumed to be the same. However, this is not generally true. A method for the estimation of the q axis characteristic from the d axis characteristic was shown. This method needs to be applied into the parameter estimation algorithm and ascertain its validity.

The operational parameters of six synchronous generators were estimated through multiple data sets for each generator. Nevertheless, it is necessary to test the proposed algorithm with a variety of generators from different utilities and different manufacturers to verify the applicability of the estimation method. A greater range of operating points needs to be examined to draw solid conclusions and possibly improve the parameter estimation procedure.

Furthermore, in order to fully explore the capabilities of this methodology, it is required to apply the proposed method in the transient case. Estimation of generator

parameters using transient data will potentially prove to be a powerful method for the better understanding of the behavior of a generator in such situations and possibly the improvement of models that are currently being used in a number of power engineering studies.

An interest from various industry members was expressed in the possibility to use the proposed method for the identification of model parameters for other types of generators such as salient pole generators and superconducting synchronous condensers. One of the future steps of this research work is to explore this possibility.

The GUI application that was developed in this research work has been designed to enable a user friendly estimation. Multiple data formats can be read and the estimation procedure is automated. Several supplementary features for further improving the appearance and operation of the application are under consideration for implementation. Such features include the display of a level of confidence and a range for the estimated parameters, and the storing of the estimated parameters over time to enable tracking of possible generator malfunction. The GUI application will be offered to a number of electric utilities for further testing and constructive criticism on its features and capabilities. After appropriate testing and enhancement of its features, it is desired to commercialize the prototype application by developing it into a software package.

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APPENDIX A

CALCULATION OF SYNCHRONOUS GENERATOR PARAMETERS

A.1 Introduction

This Appendix offers a comprehensive treatment of the calculation of generator parameters from the stability study data sheet and the generator saturation curve as provided by the generator manufacturer. The parameter calculation is based on the consideration that the model to be developed is Model 2.2 as defined in IEEE standards [83], and the derivation of the model equation as developed in Section 2.5.

As noted in Section 6.2, in order to ascertain the validity of the program it is necessary to test it with both synthetic data (user generated) and EMTP simulated noise free data. This testing necessitates the knowledge of the operating parameters of the generator under consideration. Further, when real data are used to perform the estimation, knowledge of the operational parameters will provide a higher degree of confidence in the estimated parameters.

To demonstrate the process for the calculation of generator parameters from manufacturer data, a sample generator is considered. This generator is a cross-compound generator located in the southwest U.S.A., rated at 483 MVA. The manufacturer stability study data sheet and the generator saturation curve for the generator under consideration are provided in Appendix B.

A.2 Calculation of generator parameters

Table A.1 shows the quantities that are obtained from the stability study data sheet in order to calculate the generator parameters. Furthermore, from the generator saturation curve it is possible to calculate the value of the field current at rated voltage (1

p.u.). This value is obtained from the air gap line of the no-load saturation curve in Appendix B. Hence,

$$I_{Frated} = 1226 \text{ A}. \tag{A.1}$$

TABLE A.1

Available quantities from manufacturer stability study data sheet

Quantity	Value
Rated power	483 MVA
Rated Voltage	22 kV, Y connected
x_d	1.80 p.u.
x'_{dv}	0.27 p.u.
x''_{dv}	0.19 p.u.
x_q	1.72 p.u.
x'_q	0.49 p.u.
x''_{qv}	0.19 p.u.
x_l	0.16 p.u.
x_0	0.15 p.u.
r	0.0046 p.u.
τ'_{d0}	3.7 s
τ''_{d0}	0.032 s
τ'_{q0}	0.49 s
τ''_{q0}	0.059 s

<u>Stator base quantities</u>

$$S_B = \frac{483}{3} = 161 \text{ MVA/phase}$$

$$V_B = \frac{22000}{\sqrt{3}} = 12701.706 \text{ V}$$

$$I_B = \frac{S_B}{V_B} = \frac{161 \, MVA}{12701.706 \, V} = 12675.46273 \text{ A}$$

$$R_B = \frac{V_B}{I_B} = \frac{12701.706}{12675.46273} = 1.0020704 \, \Omega$$

$$L_B = \frac{V_B}{\omega I_B} = \frac{12701.706}{2\pi 60 \, 12675.46273} = 2.6581 \times 10^{-3} \text{ H}$$

$$t_B = \frac{1}{\omega_R} = \frac{1}{2\pi 60} = \frac{1}{377} \text{radians}$$

$$L_{AD} = L_{md} = L_d - \ell_d = x_d - x_{Lm} = 1.80 - 0.16 = 1.64 \text{ p.u.}$$

$$\Rightarrow L_{md} = 1.64 L_B = 4.359284 \times 10^{-3} \text{ H}$$

$$\Rightarrow L_{AD} = 1.64 \text{ p.u} \tag{A.2}$$

To obtain M_F:

At open circuit the mutual inductance L_{aF} and the flux linkage in phase a are given by:

$$L_{aF} = M_F \cos \vartheta, \qquad \lambda_a = i_F M_F \cos \vartheta . \tag{A.3}$$

The instantaneous voltage of phase a is $v_a = i_F \omega_R M_F \sin \vartheta$, where ω_R is the rated synchronous speed [14]. Hence, the peak phase voltage is equal to $i_F \omega_R M_F$.

From the air gap line of the no-load saturation curve in Appendix B, the value of the field current at rated voltage (1 p.u.) is 1226 A. Hence,

$$M_F = \frac{V_B \sqrt{2}}{\omega i_F} \Rightarrow M_F = 38.86471277 \times 10^{-3} \text{ H}. \tag{A.4}$$

k as appears in (2.18) is a constant and is given by $k = \sqrt{3/2}$.

$$\Rightarrow kM_F = 47.59935764 \times 10^{-3} \text{ H.} \tag{A.5}$$

<u>Field base quantities</u>

$$I_{FB} = \frac{I_B}{kM_F / L_{md}} = \frac{12675.46273}{\sqrt{\dfrac{3}{2} \dfrac{38.864713 \times 10^{-3}}{4.359284 \times 10^{-3}}}} \Rightarrow I_{FB} = 1160.8435 \text{ A}$$

$$M_{FB} = \frac{kM_F}{L_{md}} L_B \Rightarrow M_{FB} = 29.02399 \times 10^{-3} \text{ H} \tag{A.6}$$

The selection of the power and voltage bases can be arbitrary. However, since it is desired to have equal mutual flux linkages in per unit between the stator and rotor circuits, then the power base is selected to be the rated power of the generator (the same for the stator power base), and therefore the voltage base is given by,

$$V_{FB} = \frac{S_B}{I_{FB}} = \frac{161 \, MVA}{1160.8435 \, A} = 138.692 \text{ kV.} \tag{A.7}$$

It should be noted that I_{FB} was appropriately calculated as above, by using the same time base for both circuits which is fixed by the rated radian frequency. The rest of the field circuit bases can be calculated as,

$$R_{FB} = \frac{V_{FB}}{I_{FB}} = \frac{140.02836 \times 10^3}{1149.7671} = 121.78846 \, \Omega$$

$$L_{FB} = \frac{k^2 M_F^2}{L_{md}^2} L_B = 0.32306 \text{ H.} \tag{A.8}$$

The parameters L_d, L_q, L_0, and r can be obtained from the stability study data sheet of Appendix B and are given by,

$$L_d = x_d \Rightarrow L_d = 1.80 \text{ p.u.}$$
$$L_q = x_q \Rightarrow L_q = 1.72 \text{ p.u.}$$
$$L_0 = x_0 \Rightarrow L_0 = 0.150 \text{ p.u.}$$
$$r_a = r_b = r_c = r = R_1 \Rightarrow r = 0.0046 \text{ p.u.} \tag{A.9}$$

First, the d axis quantities are calculated. Using the direct axis equivalent circuit of Fig. A.1, it can be shown that in per unit,

$$L_{md} = L_{AD} = L_D - \ell_D = L_F - \ell_F = L_d - \ell_d = kM_F = kM_D = M_X = 1.64 \text{ p.u.} \tag{A.10}$$
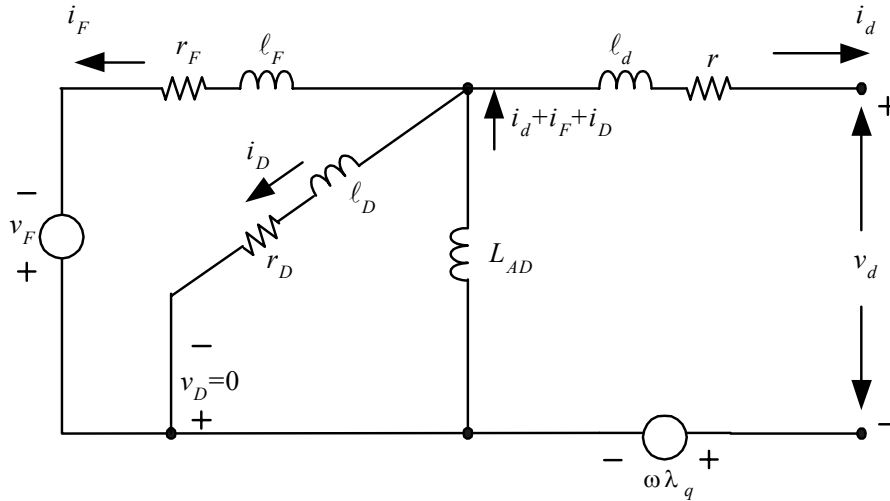
Fig. A.1. Direct axis equivalent circuit [13], [14]

Fig. A.2(a) and Fig. A.2(b) show the equivalent circuits for the d axis inductances in the transient and subtransient case respectively. By inspection of Fig. A.2(a),

$$\ell_F = L_{AD}[(L_d' - \ell_d)/(L_d - L_d')] = 1.64[(0.27 - 0.16)/(1.8 - 0.27)] = 0.11791 \text{ p.u.}$$
$$L_F = \ell_F + L_{AD} = 0.11791 + 1.64 \Rightarrow L_F = 1.75791 \text{ p.u.} \tag{A.11}$$

By inspection of Fig. A.2(b),

$$L_d'' = \ell_d + \cfrac{1}{\cfrac{1}{L_{AD}} + \cfrac{1}{\ell_D} + \cfrac{1}{\ell_F}} \Rightarrow \ell_D = \frac{L_{AD}\ell_F(L_d'' - \ell_d)}{L_{AD}\ell_F - \ell_F(L_d'' - \ell_d) - L_{AD}(L_d'' - \ell_d)}. \qquad (A.12)$$

All the values in the right hand side of (A.12) are known. Therefore,

$$\ell_D = 0.04125 \text{ p.u.}$$
$$L_D = \ell_D + L_{AD} \Rightarrow L_D = 1.68125 \text{ p.u.} \qquad (A.13)$$

(a)

(b)
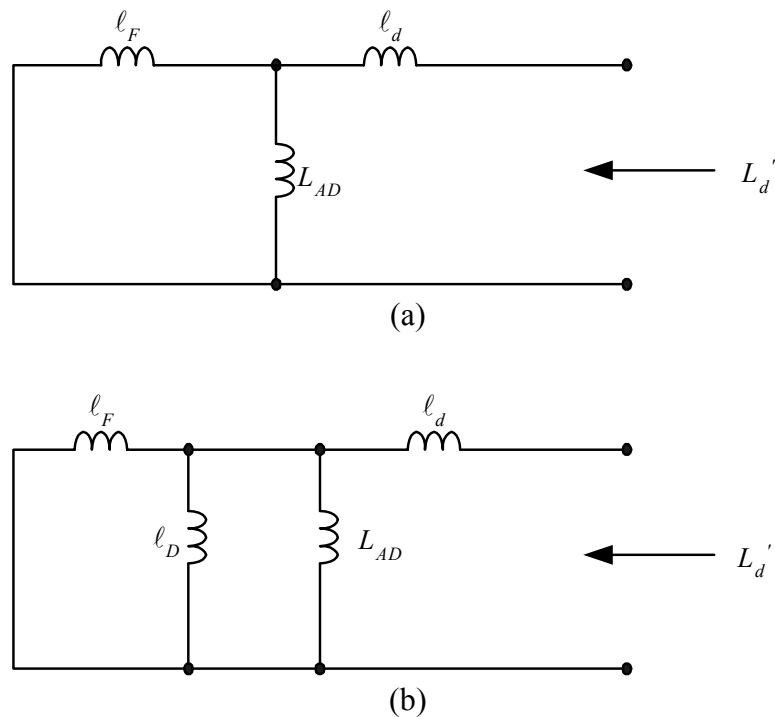
Fig. A.2. Equivalent circuits for *d* axis inductances:

(a) transient inductance, (b) subtransient inductance [13], [14]

The field resistance can be found in three ways. It may be provided in the manufacturer data sheets or even supplied by the utility in the case that it has been measured on site. A third way is to be calculated by observing that the time constant of

the transient current of the field winding is actually the d axis transient open circuit time constant τ'_{d0} [14]. Hence,

$$\tau'_{d0} = \frac{L_F}{r_F}. \tag{A.14}$$

However, in this case, the field resistance is supplied by APS and is given by,

$$r_F = 9.722 \times 10^{-4} \text{ p.u.} \tag{A.15}$$

The damper winding resistance can be estimated from the d axis subtransient time constant as shown below [14]:

$$r_D = \frac{1}{\omega_B \tau''_{d0}} \left[l_D + \frac{1}{\dfrac{1}{L_{AD}} + \dfrac{1}{l_F}} \right] \Rightarrow r_D = 0.01253759 \text{ p.u.} \tag{A.16}$$

The q axis quantities are calculated similarly to the d axis quantities. Fig. A.3 shows the quadrature axis equivalent circuit with two damper windings denoted G and Q. The leakage inductance of the quadrature axis l_q is equal to the leakage inductance of the direct axis l_d.

$$L_{AQ} = L_G - \ell_G = L_Q - \ell_Q = L_q - \ell_q = kM_G = kM_Q = M_Y = 1.56 \text{ p.u.} \tag{A.17}$$

Similar to the development of the equations for the direct axis from the transient and subtransient circuits,

$$\ell_G = L_{AQ}[(L'_q - \ell_q)/(L_q - L'_q)] = 0.4185365854 \text{ p.u.}$$
$$L_G = \ell_G + L_{AQ} \Rightarrow L_G = 1.978536 \text{ p.u.} \tag{A.18}$$

$$\ell_Q = \frac{L_{AQ}\ell_G(L_q'' - \ell_q)}{L_{AQ}\ell_G - \ell_G(L_q'' - \ell_q) - L_{AQ}(L_q'' - \ell_q)} \Rightarrow l_Q = 0.033 \text{ p.u.}$$

$$L_Q = \ell_Q + L_{AQ} \Rightarrow L_Q = 1.593 \text{ p.u.} \tag{A.19}$$
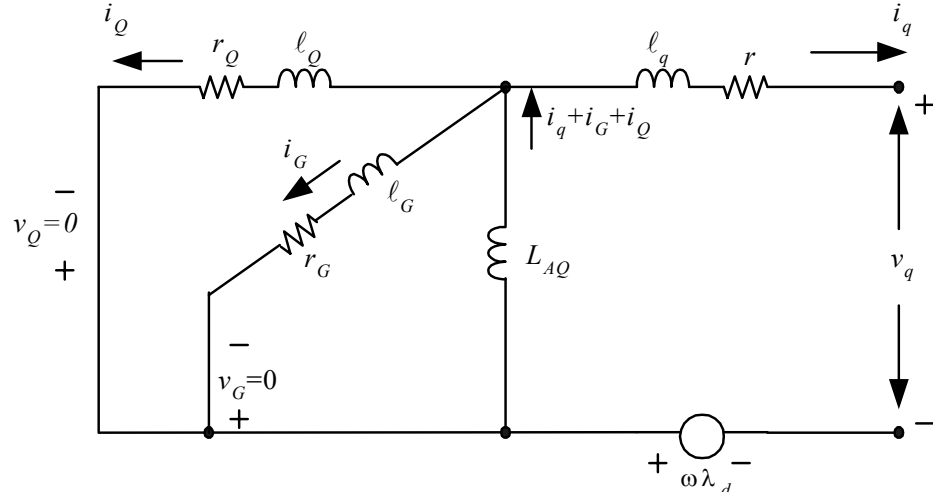
Fig. A.3. Quadrature axis equivalent circuit [13], [14]

The damper winding resistances for the q axis are given by,

$$r_G = \frac{L_{AQ} + l_G}{\omega_B \tau'_{q0}} \Rightarrow r_G = 0.0107107 \text{ p.u.} \tag{A.20}$$

$$r_Q = \frac{1}{\omega_B \tau''_{q0}}\left[l_Q + \frac{1}{\dfrac{1}{L_{AQ}} + \dfrac{1}{l_G}} \right] \Rightarrow r_Q = 0.01632 \text{ p.u.} \tag{A.21}$$

Finally, the equivalent neutral resistance and inductance are supplied by APS and are given by,

$$r_n = 100 \text{ p.u.} \tag{A.22}$$
$$L_n = 100 \text{ p.u.}$$

APPENDIX B

SATURATION CURVE AND STABILITY STUDY DATA SHEET FOR A SAMPLE

SYNCHRONOUS GENERATOR

B.1 Generator saturation curve

Fig. B.1 shows the saturation curve used in the calculation of machine constants in Appendix A. This curve is for generator FC5HP that is located at the Four Corners Generating Station of APS.
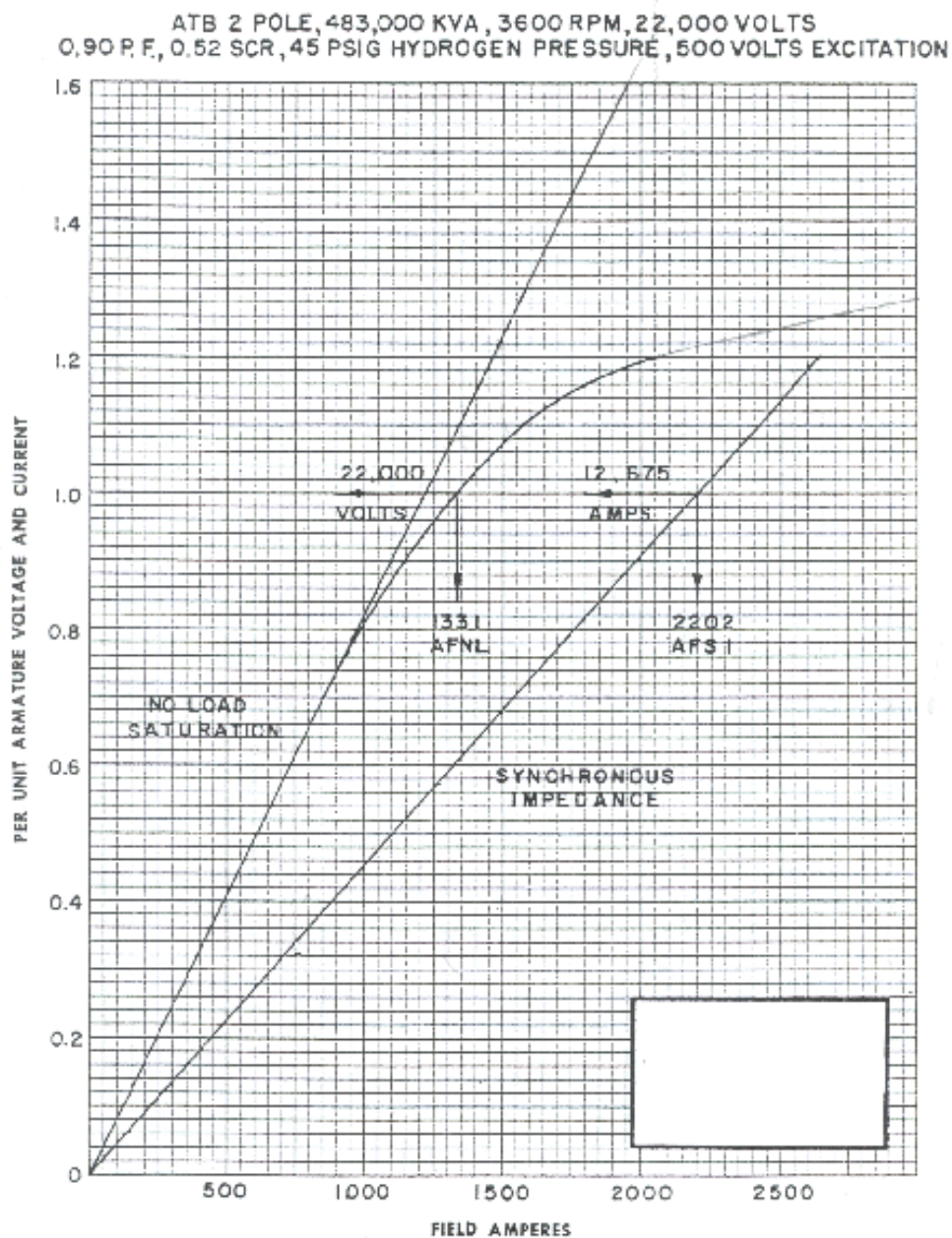
Fig. B.1. Saturation curve for the Four Corners generating station unit #5 [118]

B.2 Stability Study Data Sheet

Fig. B.2 shows the stability study data sheet that has been used to calculate the synchronous generator parameters in Appendix A.

GENERATOR DATA FOR STABILITY STUDY

Purchaser: Southern California Edison Company

Station and Unit: Four Corners #5 H.P.

Generator No.: 180I351   Turbine No.: 170I351

Req. No.: 480-52800   Rated Turbine KW: See L.P. Unit

Rated KVA: 483,000   Rated KV: 22.0

Rated P.F.: 0.90 SCR: 0.52   Rated PSIG: 45.0

Full Load Field Amperes: 3553

Sat. Curve No.: 345HA454   Vee Curve No.: 345HA455   NP No.: See L.P. Unit

Total Unit WR²: 212,000   Lb.Ft.²Rated RPM: 3600

$$H = \frac{(0.231)(WR^2)(RPM^2)(10^{-6})}{KVA\ base}\quad KW\text{-}Sec./KVA$$

Field Amperes: 4627 at rated gen. volts and amps at Q p.f. overexcited.

Field Resistance: .1357 ohms@ 125 C° .0980 ohms@ 25 C°

Type of Exciter: ~~MOTOR GENERATOR SUBBED UNDER CORRESPONDING GENERATOR~~, ALTHYREX

Voltage Response: 2.5   Amplidyne KW: None

Type of voltage regulator: ~~TRANSISTOR REGULATOR CORRESPONDING GENERATOR~~ SA410

X_d	1.80		X_q	1.72
X'_{di}	.285		X'_q	.490
X'_{dv}	.270		X_o	.150
X''_{di}/X''_{qi}	.220/.220		$X_L=X_{La}$ Steam only	.160
X''_{dv}/X''_{qv}	.190/.190		X_p hydro only	- - - - - -
$X_2=\frac{1}{2}(X''_{dv}+X''_{qv})$	.190		R_2	.024
R_1	.0046			
T'_{do}	3.7		T'_{qo}	.49
T''_{do}	.032		T''_{qo}	.059
$T_a=T_{a3}$	.15			

Steam Turbine max. expected load (KW*)   Refer to L.P. Unit I352   KW.

Fraction of Power in HP Turbine (f): 0.30

Steam Bowl Volume (V_B): 123.8   Ft.³.

By: R.N. Greene

Date: October 13, 1971

Rev.#7-(8/19/71) smm

Fig. B.2. Stability study data for the Four Corners generating station unit #5 [119]

APPENDIX C

OVERVIEW OF PROPOSED MAGNETIC SATURATION FUNCTIONS

C.1 Introduction

In order to implement the saturation of generator inductances effectively, it is necessary to model the saturation curve as supplied by the manufacturer as accurately as possible. As mentioned in Chapter 3, various saturation functions have been proposed in the literature with varying degrees of accuracy. This appendix examines a number of proposed saturation models (both existing models and new proposed models). The comparison between the computed saturation curve and the actual saturation curve will indicate the best saturation function out of the proposed models.

C.2 Proposed saturation functions

A number of candidate generic models are examined in this section. These models are depicted in Table C.1. Other candidate models have also been examined but only the three proposed models of Table C.1 will be discussed for demonstration purposes.

TABLE C.1

Candidate saturation function models

Model number	Saturation function
1	$\lambda_I = A \cdot e^{B(V_t - V_0)}$
2	$\lambda_I = a(V_t)^4 + b(V_t)^2 + c$
3	$\lambda_I = a\cosh(V_t - V_0) + b\sinh(V_t - V_0) + c$

C.3 Comparison of saturation functions to the actual saturation curve

Fig. C.1 depicts the actual saturation curve for a synchronous generator. Both the air-gap line and the open circuit characteristic (OCC) are shown. The saturation curve was duplicated from the actual saturation curve of Appendix B.

In order to plot the saturation functions from the proposed models, the constants in the model equations need to be assigned a numerical value. V_0 is the threshold saturation constant as mentioned in Chapter 3, and can be obtained by direct observation of the saturation curve in Fig. C.1. λ_I is the saturation function and it is assigned the value of zero for $V_t < V_0$ in order to obtain the air-gap line up to V_0. The constants A, B, a, b, and c are calculated by using data from the actual saturation curve. It should be noted that instead of terminal voltages, flux linkages may also be used as described in Chapter 3. Model 1 needs two data points to create a system of two equations in two unknowns, while models 2 and 3 need three data points.

The results of the simulation of the three models are depicted in Figs C.2-C.4. Fig. C.2 shows the saturation curve obtained using the first model. This is the model that is used extensively to model saturation in contemporary practices. Comparison to the saturation curves obtained from the other models in Figs C.3 and C.4 verifies that this model is superior to any of the other models that have been proposed.
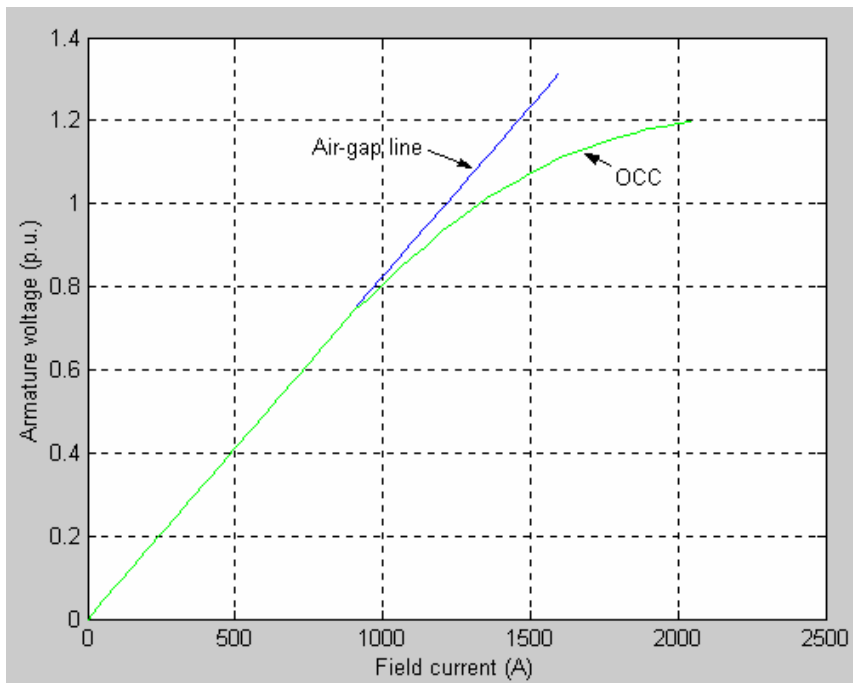
Fig. C.1. Actual saturation curve for a synchronous generator
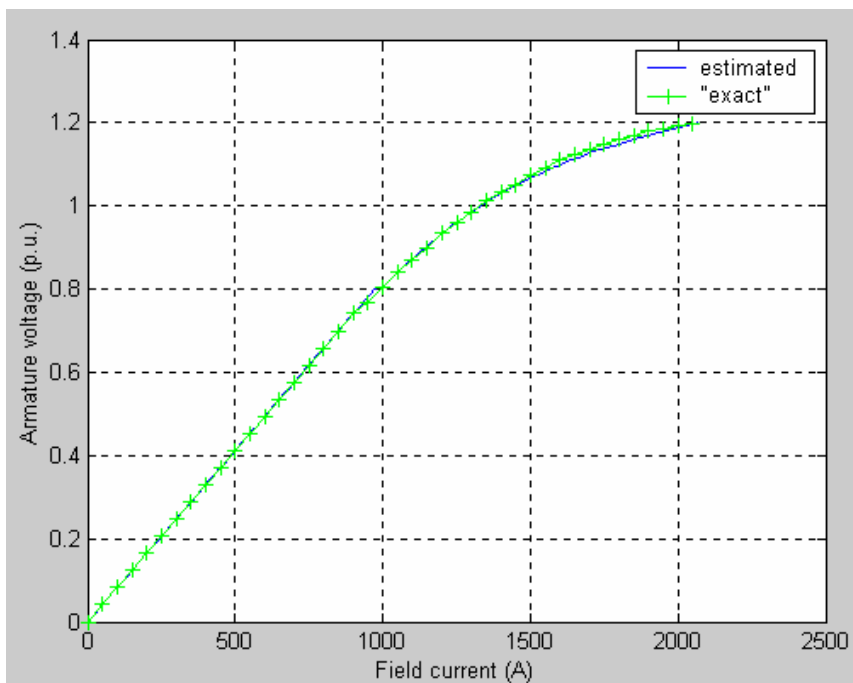
Fig. C.2. Model 1 saturation curve as compared to the manufacturer saturation curve
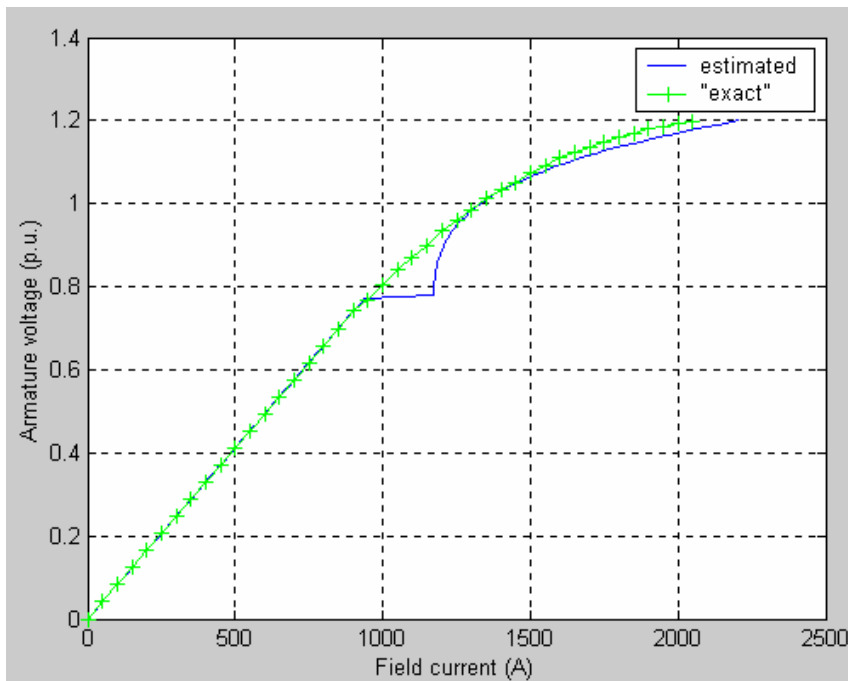
Fig. C.3. Model 2 saturation curve as compared to the manufacturer saturation curve
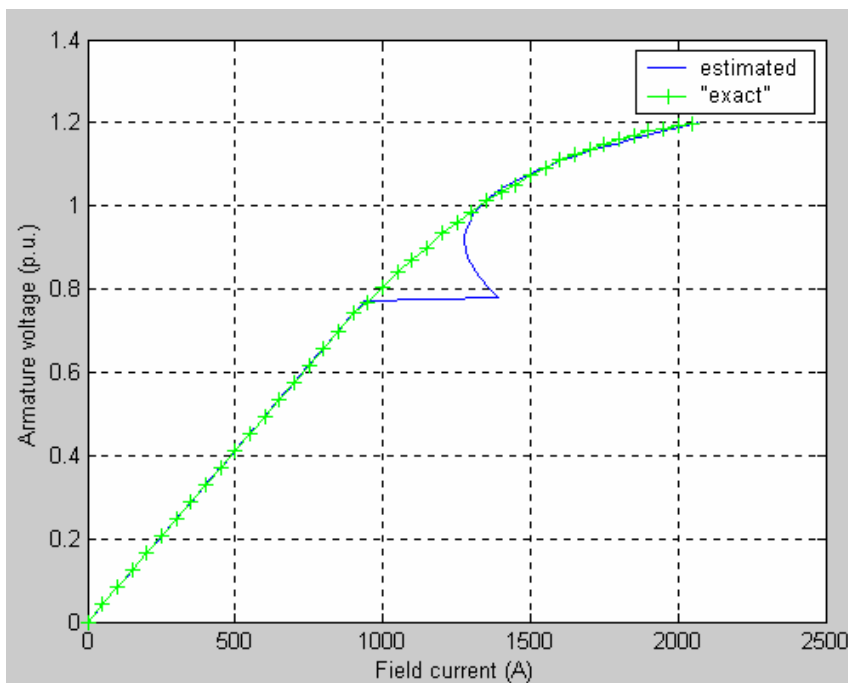
Fig. C.4. Model 3 saturation curve as compared to the manufacturer saturation curve

APPENDIX D

SELECTION OF THE NUMERICAL DIFFERENTIATION FORMULA

D.1 Selection of the numerical differentiation formula

The synchronous machine model of (2.22) and (3.11) raises the need to approximate the derivative of the measured signals by an appropriate differentiation formula. In order to select a suitable differentiation formula, a scalar differential equation was selected to perform a number of case studies. These case studies include the testing of various candidate methods, as well as the estimation of the parameters in both noise free and noise contaminated environments. The results obtained by these case studies will give some indication or reassurance for the most appropriate method to be utilized in the actual model of the synchronous machine.

Assume that it is desired to estimate parameters a and b in a model of the form,

$$\dot{x} = ax + b, \tag{D.1}$$

where x is considered to be a measured scalar signal. This model is the scalar equivalent model of the model developed for the purposes of this dissertation. Let $a = -1$ and $b = 1$, so that the differential equation becomes,

$$\dot{x} = -x + 1, \tag{D.2}$$

which has the solution,

$$x(t) = e^{-t} + 1. \tag{D.3}$$

Noise free data can be constructed by the solution of (D.3) and noise can be added as necessary to create data with various signal to noise ratios (SNRs). Moreover, since the time vector t can be arbitrarily selected, a number of case studies may be performed with different time steps to enable comparison of all methods depending on both the level of noise and the time step used.

Tables D.1 and D.2 show two representative case studies. The first case study considers noise free data with a time step of 0.1 s, while the second case study considers data that have been contaminated with noise to create a SNR of 200 and that also have a time step of 0.1 s.

TABLE D.1

Estimation of parameters for $\Delta T = 0.1$ and SNR $= \infty$ (case study S-NF-02-13)

Method	$\hat{a}$	$\hat{b}$
Trapezoidal rule	-0.9992	0.9992
Simpson's rule	-1.0000	1.0000
Forward difference formula	-0.9516	0.9516
Third order difference form.	-0.9998	0.9998
Fifth order diff. formula	-1.0000	1.0000

TABLE D.2

Estimation of parameters for $\Delta T = 0.1$ and SNR $= 200$ (case study S-NC-02-14)

Method	$\hat{a}$	$\hat{b}$
Trapezoidal rule	-1.01707	1.01719
Simpson's rule	-1.02162	1.01933
Forward difference formula	-0.99029	1.00097
Third order difference form.	-1.15118	1.24195
Fifth order diff. formula	-1.11691	1.12961

Tables D.3 and D.4 compare the two case studies that are displayed in Tables D.1 and D.2. In particular, the percent errors for parameters a and b are computed for each method, and for both noise free and noise contaminated measurements. Table D.5 ranks the five methods in order of increasing error. The top ranked method exhibits the smaller percent error in each case study.

TABLE D.3

Comparison of percent relative error in estimating parameter a for case studies

S-NF-02-13 and S-NC-02-14

	Simpson's	Trapezoidal	1st order	3rd order	5th order
No noise	0	0.08	4.84	0.02	0
Noise	2.16	1.71	0.97	15.12	11.7

TABLE D.4

Comparison of percent relative error in estimating parameter b for case studies

S-NF-02-13 and S-NC-02-14

	Simpson's	Trapezoidal	1st order	3rd order	5th order
No noise	0	0.08	4.84	0.02	0
Noise	1.93	1.72	0.10	24.2	12.96

TABLE D.5

Ranking of the methods in order of increasing error

NO NOISE	NOISE
1. Simpson's	1. Forward difference
2. Fifth order	2. Trapezoidal
3. Third order	3. Simpson's
4. Trapezoidal	4. Fifth order
5. Forward difference	5. Third order

A number of other case studies were performed for various signal to noise ratios. Fig. D.1 shows the relative error in parameter *a* for a time step of 0.1 s. Fig. D.2 shows the relative error in parameter *a* for a time step of 0.2 s, while Fig. D.3 shows the relative error in parameter *a* for a time step of 0.05 s. From the three graphs it can be seen that in general the Trapezoidal and the Simpson's rule give better estimates at low signal to noise ratios (i.e. in heavily polluted measurements). However, the errors obtained at these levels are in the order of 20% or higher, and therefore the results are not useful unless a noise filter is introduced. Therefore, one should direct the attention to slightly higher signal to noise ratios where the estimates are considered reasonable.

For the case studies where the signal to noise ratios are in the order of 400 and above, three methods seem to prevail: the Trapezoidal, the Simpson's, and the forward difference formula. The forward difference formula seems to offer better results than the other two methods. In conjunction with the ranking of Table D.5 (where the forward

difference formula was ranked as the best in a noisy environment), a decision can be made for the implementation of the forward difference formula for the numerical differentiation of the problem at hand.
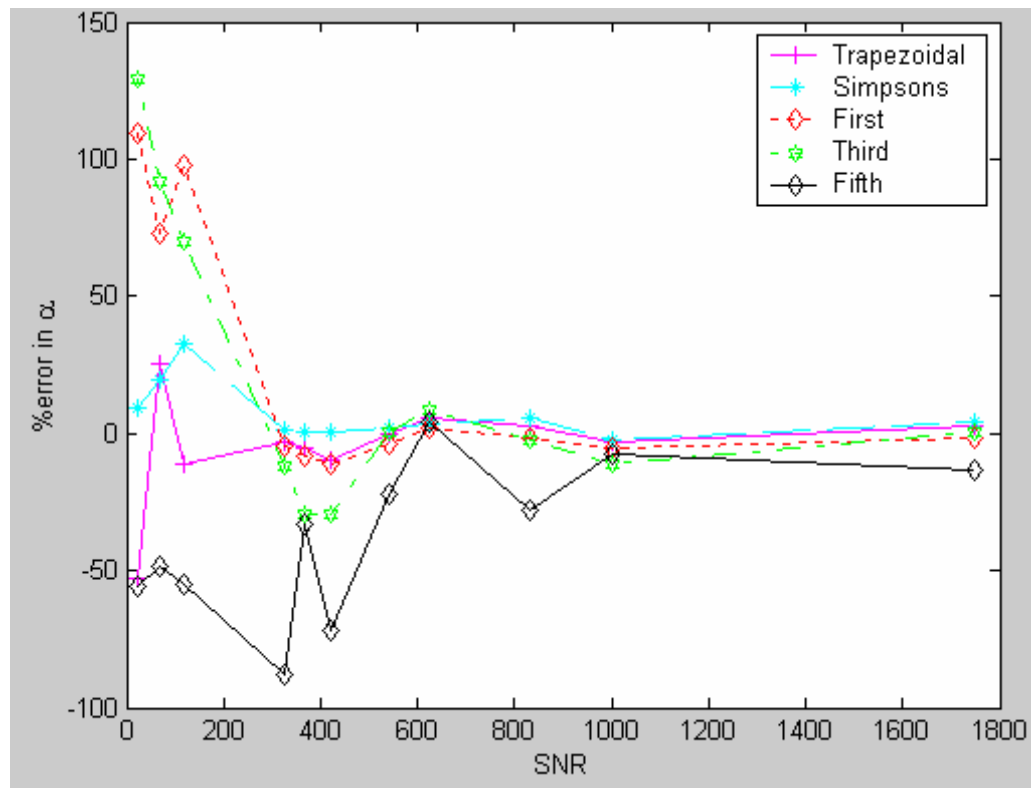
Fig. D.1. Relative error in parameter a for $\Delta T = 0.1$ and for various SNRs
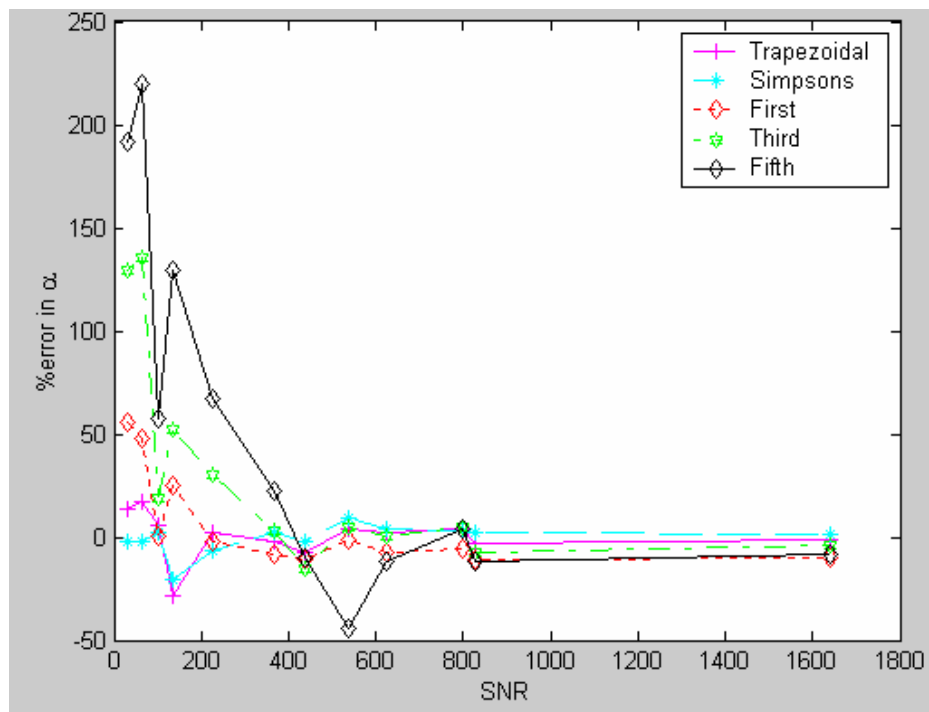
Fig. D.2. Relative error in parameter *a* for $\Delta T = 0.2$ and for various SNRs
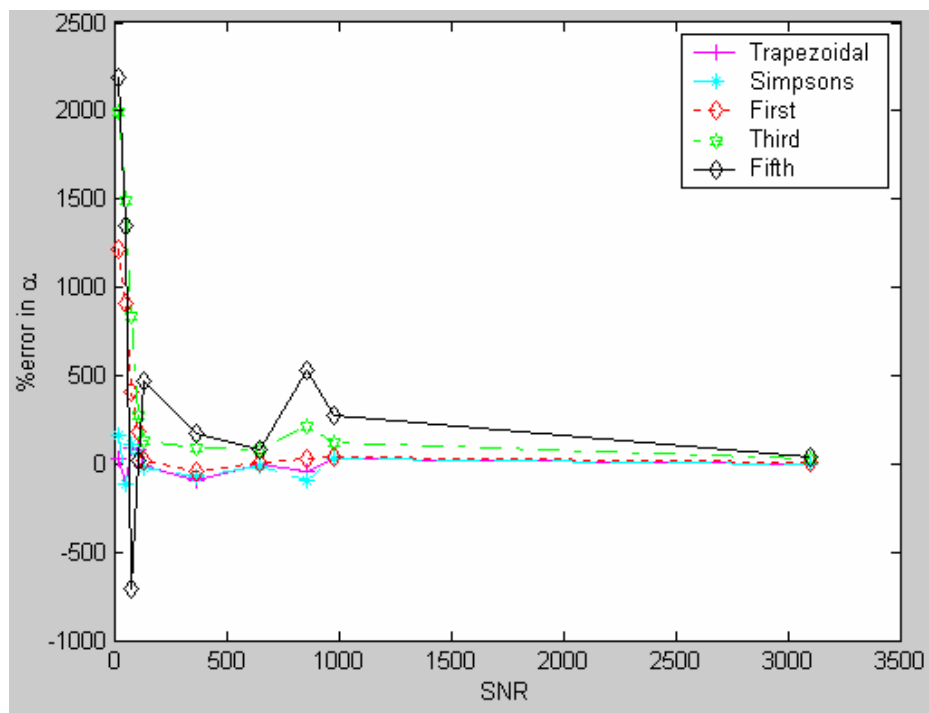
Fig. D.3. Relative error in parameter *a* for $\Delta T = 0.05$ and for various SNRs

APPENDIX E

DATA FORMATS SUPPORTED BY THE *ESTIMATOR*

E.1 Introduction

As mentioned in Chapter 9, there are two data formats that are supported by the *Estimator*: an *abc* data format that can be read as a text file (.txt extension), and a combination of two data files that follow the COMTRADE format of the IEEE Std. C37-111.1999 (.cfg and .dat extensions) [116]. The purpose of having two data formats supported by the *Estimator* is to accommodate all possible configurations of data files currently used by utilities. The COMTRADE format data file is the output of digital fault recorders (DFRs) that are typically used for recording measurements at the terminals of a synchronous generator, while .txt files can be generated using a variety of word processors. An example of each data format is shown in Sections E.2 and E.3 respectively.

E.2 Text file (*abc*) data format

Input data in the form of a text file (.txt extension) is a convenient data format for data that have been preprocessed after the required measurements have been obtained from the data recording device. The data are arranged in columns in the order shown in Table E.1. There are nine columns that are required. The first column contains the time measurement, while the remaining eight columns contain the stator and field voltages and currents.

TABLE E.1

Arrangement of data in the text format data file

Time (s)	V_{ab} (kV)	V_{bc} (kV)	V_{ca} (kV)	V_F (V)	I_a (kA)	I_b (kA)	I_c (kA)	I_F (kA)
0	-29.4	20.9	8.5	274.0	-2.37	1.23	1.05	1.19
$4.70x10^{-4}$	-30.3	16.6	13.6	114.0	-2.46	0.97	1.40	1.16
$9.40x10^{-4}$	-30.2	12.0	18.2	-60.7	-2.37	0.53	1.75	1.12
$1.41x10^{-3}$	-29.1	6.8	22.2	-231.0	-2.19	0.09	2.02	1.08
$1.88x10^{-3}$	-27.0	1.3	25.4	311.0	-1.93	-0.44	2.28	1.18

E.3 COMTRADE data format

The second option that is supported by the *Estimator* is the format that is based on the COMTRADE data format which is an IEEE standard. A DFR outputs two data files, the first being a configuration data file containing general information for the signals, while the second file is a .dat file and contains the measurements at the generator terminals.

A sample configuration file can be seen in Fig. E.1. A thorough explanation of each item in the configuration file is offered in [116]. In general, the first two lines in the file contain the heading and the number of channels that were used to record data. The next section of the file that is arranged in numerical order contains information for each measurement. This information contains the channel number, the generator unit under study, the quantity that is being measured in that channel, the unit of measurement (e.g. V

or kV), the multiplication factor to be used for each signal, and the offset (if any) because of the DFR settings.

Finally, the last section of the configuration file contains the frequency of the generator, the sample rate and total number of samples, the start and end times and dates of the measurement, and the data file type (e.g. ASCII or binary).

```
Ben664_FC4&5,664,1999
8,8A,0D
1,U5 HP Ia     ,A,0,kA  ,0.0026987161,0.0000000000,0,-32767,+32767,1,1,P
2,U5 HP Ib     ,B,0,kA  ,0.0026987161,0.0000000000,0,-32767,+32767,1,1,P
3,U5 HP Ic     ,C,0,kA  ,0.0026987161,0.0000000000,0,-32767,+32767,1,1,P
4,U5 HP Vfd    ,,,V  ,0.0518153496,0.0000000000,0,-32767,+32767,1,1,P

5,U5 Vab Gen   ,A,0,kV  ,0.0018998961,0.0000000000,0,-32767,+32767,1,1,P
6,U5 Vbc Gen   ,B,0,kV  ,0.0018998961,0.0000000000,0,-32767,+32767,1,1,P
7,U5 Vca Gen   ,C,0,kV  ,0.0018998961,0.0000000000,0,-32767,+32767,1,1,P
8,U5 HP Ifd    ,,,A  ,0.2072613984,0.0000000000,0,-32767,+32767,1,1,P
60
1
10000.000,3219
25/07/2002,13:00:01.238600
25/07/2002,13:00:01.358600
ASCII
1
```

Fig. E.1. Sample configuration (.cfg) data file following the COMTRADE format

The configuration file is associated with a data file with a .dat extension. These are produced simultaneously by the recording device. The .dat file contains integer measurements of the signals. The column numbers in the .dat file correspond to the channel number in the .cfg file starting from column 3. Column 1 contains the sample number, while column 2 contains the timestamp. From the timestamp the time of each measurement can be obtained by,

$$t = (timestamp) \times (timemult) \ \mu s \,, \tag{E.1}$$

where *timemult* is the timestamp multiplication factor obtained from the last line of the

.cfg file. A sample .dat file can be seen in Fig. E.2.

```
 1,           0, -5104,  -192,  5184, 11328, -8192, -8128, 16256, 12240
 2,         100, -4976,  -432,  5296, 10432, -7664, -8640, 16240, 12304
 3,         200, -4864,  -640,  5392,  9840, -7104, -9168, 16208, 12352
 4,         300, -4736,  -864,  5472,  9136, -6528, -9696, 16144, 12368
 5,         400, -4592, -1088,  5552,  8336, -5952,-10176, 16048, 12384
 6,         500, -4448, -1312,  5632,  7680, -5376,-10656, 15952, 12400
 7,         600, -4304, -1504,  5696,  6912, -4784,-11104, 15824, 12400
 8,         700, -4144, -1728,  5760,  6112, -4192,-11552, 15664, 12384
 9,         800, -3984, -1936,  5808,  5376, -3600,-11968, 15488, 12384
10,         900, -3824, -2128,  5840,  4624, -3008,-12384, 15296, 12368
11,        1000, -3664, -2336,  5872,  3840, -2416,-12768, 15104, 12352
12,        1100, -3488, -2528,  5904,  3072, -1824,-13152, 14880, 12320
13,        1200, -3312, -2720,  5904,  2304, -1216,-13504, 14640, 12288
14,        1300, -3120, -2912,  5920,  1520,  -608,-13856, 14384, 12272
```

Fig. E.2. Sample data (.dat) file following the COMTRADE format

APPENDIX F

PARAMETER ESTIMATION RESULTS USING ACTUAL DATA

F.1 Estimation of parameters for two steam turbine generators

Parameter estimation results in Chapter 8 for generators FC5HP, GT1, and GT2 indicated good correlation between manufacturer supplied parameters and estimated parameters at different operating points. The increase in the excitation levels of the gas turbines GT1 and GT2 indicated a general decreasing trend in the estimated mutual inductances. This was expected from synchronous generator theory. Further, the correction factor applied for saturation resulted in unsaturated inductances with very small variations.

This appendix offers parameter results from two steam turbine generators located at the Redhawk generating station of APS. Seven data sets from generator ST1 and one data set from generator ST2 are analyzed. The two generators are rated at 213.7 MVA and 18 kV. The manufacturer supplied inductances L_{AD} and L_{AQ} are 1.924 p.u. and 1.79 p.u. respectively. The characteristics for the two generators are described in Table 3.1.

The analysis procedure is similar to the one provided in Chapter 8. Three parameters were estimated from each data set: L_{AD}, L_{AQ}, and r_F. The operating point of the generator for each data set is shown, as well as the field current. Table F.1 depicts the parameter estimation results for the eight data sets obtained from the two units, as well as information regarding the operating point, the estimated inductances corrected for saturation, and the deviation from the manufacturer supplied parameters.

TABLE F.1

Parameter estimation results for Redhawk steam turbines 1 and 2*

Case study	Unit #	$\hat{L}_{AD}$ (p.u.)	$\hat{L}_{AQ}$ (p.u.)	$\hat{r}_F$ (p.u.)	K_{sd}	i_F (A)	P (MW)	Q (MVAr)	$\hat{L}_{ADu}$ (p.u.)	$\hat{L}_{AQu}$ (p.u.)	% deviation	
											L_{AD}	L_{AQ}
R-NC-03-26	ST1	1.5243	1.7871	$6.6587x10^{-4}$	0.9285	1015.8	167.13	24.28	1.6417	1.9247	14.7	7.5
R-NC-03-27	ST1	1.5891	1.7862	$6.3587x10^{-4}$	0.8842	819.85	123.91	6.90	1.7972	2.0201	6.6	12.9
R-NC-03-28	ST1	1.5734	1.752	$6.2501x10^{-4}$	0.8864	890.22	138.62	13.29	1.7750	1.9765	7.7	10.4
R-NC-03-29	ST1	1.6843	1.7956	$5.5220x10^{-4}$	0.8831	650.36	61.34	4.19	1.9073	2.0333	0.9	13.6
R-NC-03-30	ST1	1.6015	1.7021	$6.2198x10^{-4}$	0.8834	855.89	125.55	15.49	1.8129	1.9268	5.8	7.6
R-NC-03-31	ST1	1.5646	1.8458	$6.9660x10^{-4}$	0.8833	882.95	140.35	11.25	1.7713	2.0897	7.9	16.7
R-NC-03-32	ST1	1.5401	1.814	$7.3236x10^{-4}$	0.8889	918.56	146.58	15.79	1.7326	2.0407	9.9	14.0
R-NC-03-33	ST2	1.5252	1.7852	$6.5160x10^{-4}$	0.8802	930.34	144.49	16.75	1.7328	2.0281	9.9	13.3
Mean (μ)				$6.4768x10^{-4}$					1.7714	2.0050		
Standard deviation (σ)				$2.55 x10^{-9}$					0.0051	0.0029		

* From the manufacturer data sheet: L_{AD} = 1.924 p.u., L_{AQ} = 1.79 p.u., while r_F is unavailable

It should be noted that there are two potential factors that may affect the results obtained for these two particular generators. Firstly, the stator resistance for the two units is not supplied by the manufacturer. Therefore, an arbitrary (but typical) value for the resistance needs to be used in the estimation process. The estimates will certainly be affected by this inaccuracy, since the calculation of the power angle δ and some of the elements in the measurement vector z depend or the stator resistance. Secondly, the field voltage and current multiplication factors from the DFR are reversed in the configuration data file. Although this is corrected after the data files are read by the *Estimator*, the calibration of the channels is probably slightly off. This will mostly affect the estimate of the field resistance, but will also have an impact on the other estimated parameters.

Fig. F.1 shows the change in the estimated direct axis mutual inductance L_{AD} with the field current. A linear regression model is fitted to observe the trend in the estimated inductance over increasing saturation levels. A significant decrease in the apparent value of the inductance is observed as the generator is driven to higher operating points.

Fig. F.2 compares both the saturated and the unsaturated values of L_{AD} for all case studies for the steam turbine generators. The stacked column graph shows the estimated parameters and the correction for saturation. The unsaturated values of L_{AD} have a mean of 1.7714 p.u. and a standard deviation of 0.0051 p.u.

The results of each case study for the quadrature axis mutual inductance L_{AQ} are summarized in Figs F.3 and F.4. The estimated values of the quadrature axis mutual inductance at different operating points are shown in Fig. F.3. In this case there is no apparent trend in the saturated values of the inductance. There are four leverage points

(two above the mean value of the inductance and two below), causing the regression model to be approximately a constant. The mean of the unsaturated quadrature axis mutual inductance is 2.005 p.u. and the standard deviation is 0.0029 p.u. A comparison between the unsaturated values of L_{AQ} at each operating point is offered in Fig. F.4, where the saturated inductances are corrected for saturation using the appropriate saturation factors at each operating point.
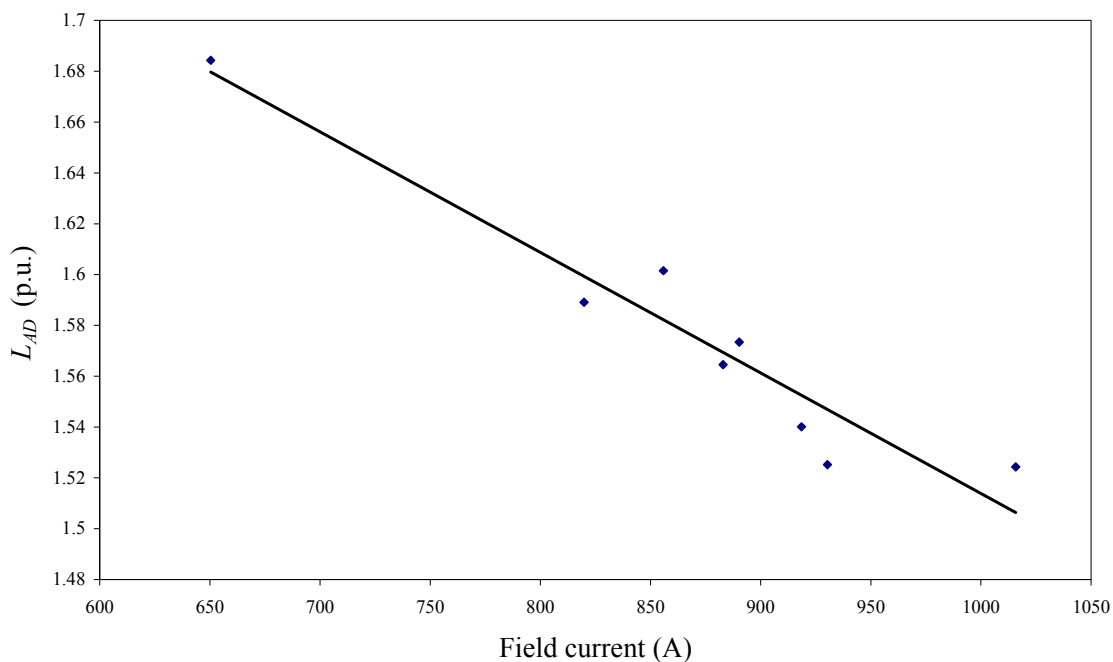
Fig. F.1. Change of L_{AD} with operating point for Redhawk steam turbine generators
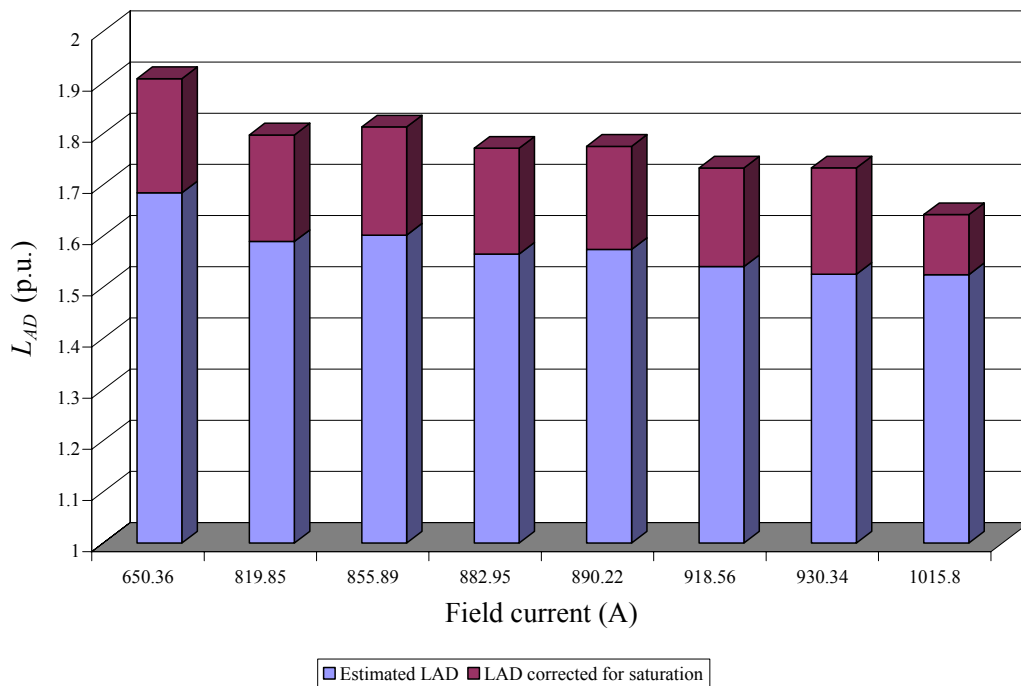
Fig. F.2. Saturated and unsaturated values of L_{AD} for Redhawk steam turbine generators
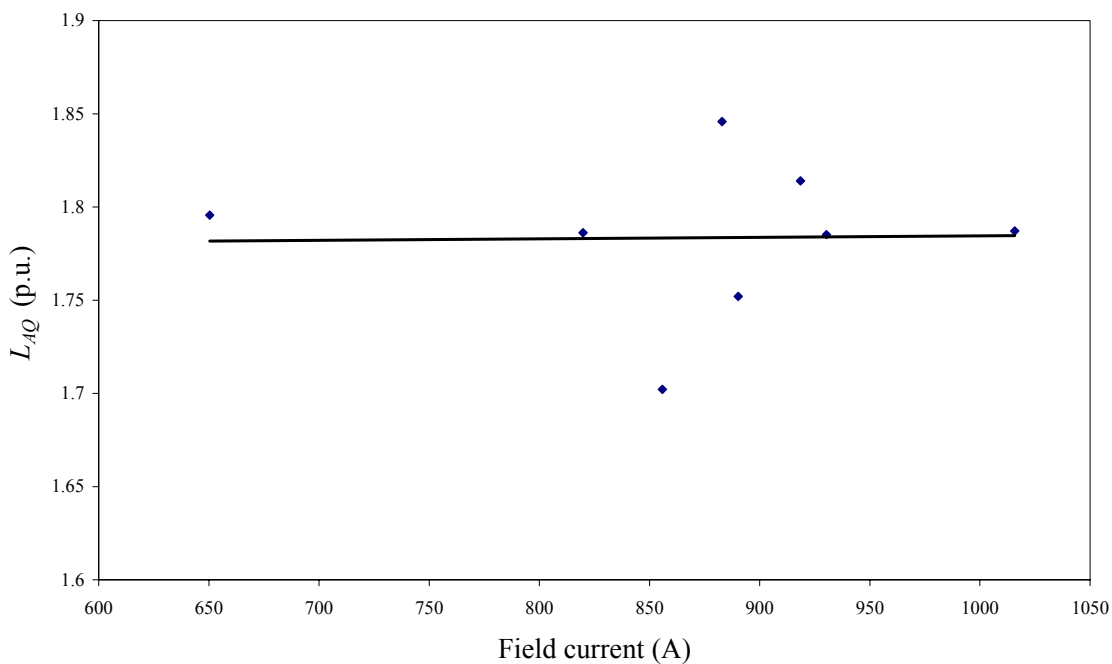
Fig. F.3. Change of L_{AQ} with operating point for Redhawk steam turbine generators
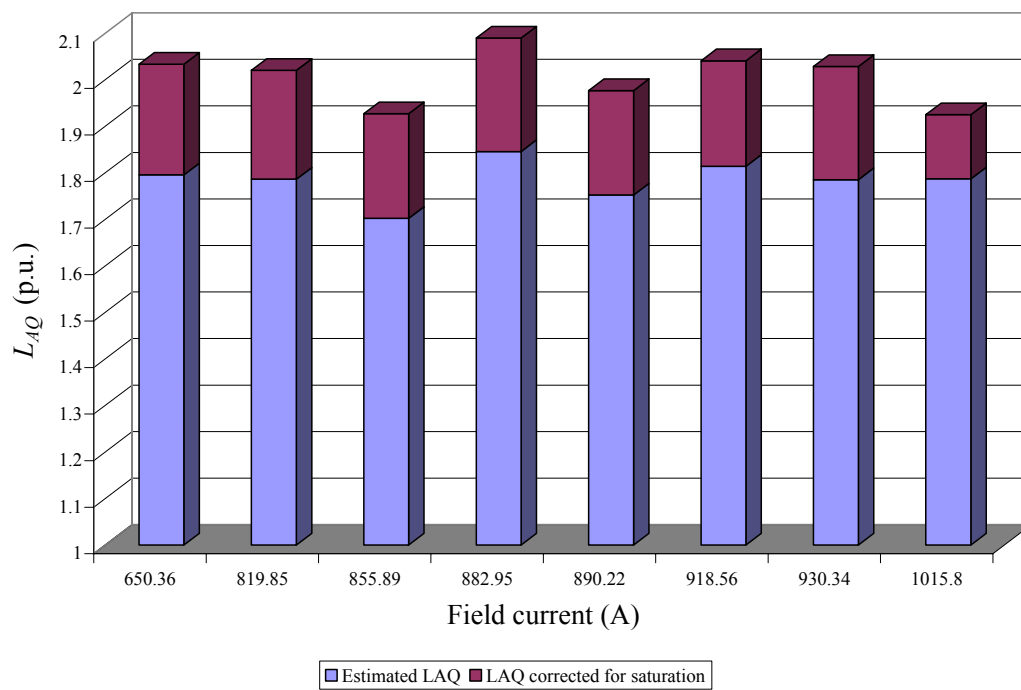
Fig. F.4. Saturated and unsaturated values of L_{AQ} for Redhawk steam turbine generators

APPENDIX G

MATLAB CODE FOR PARAMETER ESTIMATION USING ACTUAL

MEASUREMENTS

```
%***********************************************************************************
%*Estimation of synchronous generator parameter using actual DFR measurements      *
%*As an example, this m-file estimates the parameters of Redhawk GT1 gas turbine    *
%*This file estimates the generator parameters per model 2.2x                       *
%*One damper winding in d-axis, and two damper windings in q-axis                   *
%*All inductances are written in terms of LAD, LAQ, and leakage inductances         *
%*Copyright: Elias Kyriakides                                                       *
%*Last updated: November 2, 2003                                                    *
%***********************************************************************************

clear all;

mvab = (213.7e6)/3; %MVA base
kvb = 18000/sqrt(3); %voltage base
ib = mvab/kvb;          %current base

cfb = 560.8695433; %field current base
vfb = mvab/cfb;     %field voltage base

ns = 7; %no. of states

%Read data file
dummy = csvread('C:\My Documents\RESEARCH\external data\realdataRedhawk\GT1A.dat');


%Input multiplication factors from .cfg file
   m1 = 0.0014249221; %Vab
   m2 = 0.0014249221; %Vbc
   m3 = 0.0014249221; %Vca
   m4 = 0.0013817426; %Ia
   m5 = 0.0013817426; %Ib
   m6 = 0.0013817426; %Ic
   m7 = 0.1036306992; %IF
   m8 = 0.0259076748; %VF
   timemult = 1;     %time multiplication factor

   t(:,1)=dummy(:,2);
   nt = length(t1);


%To initialize iabc and vabc
   vabc=zeros(nt,ns);
   iabc=zeros(nt,ns);

   vabc(:,1)=dummy(1:nt,3); %phase A-B line-line voltage
   vabc(:,2)=dummy(1:nt,4); %phase B-C line-line voltage
   vabc(:,3)=dummy(1:nt,5); %phase C-A line-line voltage
   iabc(:,1)=dummy(1:nt,6); %phase A current
   iabc(:,2)=dummy(1:nt,7); %phase B current
   iabc(:,3)=dummy(1:nt,8); %phase C current

   ifl(:,1)=dummy(1:nt,9); %field current
   vfl(:,1)=dummy(1:nt,10);  %field voltage
```

%Multiply read data by the relevant multiplication factors:

```
t = t*(timemult*1E-6);  %readings in microseconds
vabc(:,1) = vabc(:,1)*m1*1000; %readings in kV
vabc(:,2) = vabc(:,2)*m2*1000; %readings in kV
vabc(:,3) = vabc(:,3)*m3*1000; %readings in kV
iabc(:,1) = iabc(:,1)*m4*1000;  %readings in kA
iabc(:,2) = iabc(:,2)*m5*1000;  %readings in kA
iabc(:,3) = iabc(:,3)*m6*1000;  %readings in kA

ifl = ifl*m7;
vfl = vfl*m8;

vfl=-vfl; %in the Park's voltage equations field voltages are negative


%Field measurements filters

%Plots of unfiltered quantities
plot(t,vfl)
title('Plot of VF data')
xlabel('time (s)')
ylabel('VF')
figure;

plot(t,ifl)
title('Plot of iF data')
xlabel('time (s)')
ylabel('iF')
figure;

%and their FFT:

dt=t(2)-t(1);        % define time between samples

N=nt;   %define number of samples

h=fft(vfl)/N;           % take fft
h=fftshift(h);           % rotate to center zero frequency
Fnq=1/(2*dt);            % calc maximum frequency
T=N*dt;              % calc period of waveshape
df=1/T;              % calc frequency resolution
fq=-Fnq+[0:(N-1)]'*df +df/2;    % create frequency vector for plot
mag=abs(h);             % magnitude of fft
plot(fq(1:N), mag,'d'); ylabel('VF FFT Magnitude')
figure;

vfl_unfilteredFFT_zerofrcomp=real(mean(vfl));


h=fft(ifl)/N;          % take fft
h=fftshift(h);           % rotate to center zero frequency
Fnq=1/(2*dt);            % calc maximum frequency
```

```
T=N*dt;                % calc period of waveshape
df=1/T;                % calc frequency resolution
fq=-Fnq+[0:(N-1)]'*df +df/2;    % create frequency vector for plot
mag=abs(h);            % magnitude of fft
plot(fq,mag,'d'); ylabel('IF FFT Magnitude')
figure;

ifl_unfilteredFFT_zerofrcomp=real(mean(ifl));


%Filter field voltage:

%Find order and normalized frequency using the buttord function
fN=1/(2*dt); %Nyquist frequency

fc=50; %cutoff frequency
fstop=1000;% frequency where stopband begins

Wp=fc/fN; %passband corner frequency
Ws=fstop/fN; %stopband corner frequency
Rp=0.01; %passband ripple in dB (max permissible passband loss in dB)
Rs=40; %stopband attenuation in dB (number of dB the stopband is down from the passband)

[n, Wn]=buttord(Wp, Ws, Rp, Rs);
[b,a]=butter(n, Wn); %order and normalized cutoff frequency

vflfiltered=filtfilt(b,a,vfl); %zero phase filtering

%re-filter
for y=1:50
   vflfiltered=filtfilt(b,a,vflfiltered);
   y=y+1;
end




%Filter field current

fc=20; %cutoff frequency
fstop=130;% frequency where stopband begins

Wp=fc/fN; %passband corner frequency
Ws=fstop/fN; %stopband corner frequency
Rp=0.001; %passband ripple in dB (max permissible passband loss in dB)
Rs=50; %stopband attenuation in dB (number of dB the stopband is down from the passband)

[n, Wn]=buttord(Wp, Ws, Rp, Rs);
[b,a]=butter(n, Wn); %order and normalized cutoff frequency

iflfiltered=filtfilt(b,a,ifl);
```

```
%re-filter
for y=1:150
    iflfiltered=filtfilt(b,a,iflfiltered);
    y=y+1;
end


%Plot FFT of field voltage and current
N=nt;
h=fft(vflfiltered)/N;
h=fftshift(h);
Fnq=1/(2*dt);          % calc maximum frequency
T=N*dt;                % calc period of waveshape
df=1/T;                % calc frequency resolution
fq=-Fnq+[0:(N-1)]'*df +df/2;   % create frequency vector for plot
mag=abs(h);
plot(fq,mag,'d'); ylabel('VF filtered FFT magnitude using zero phase filtering (final filter)');
xlabel('frequency')
axis([-80 80 0 inf])
figure;


%time data
plot(t(1:N), real(vflfiltered)) ;  ylabel('VF filtered time data with zero phase filtering'); xlabel('time')
figure;

vfl_filteredFFT_zerofrcomp=real(mean(vflfiltered));




h=fft(iflfiltered)/N;
h=fftshift(h);
Fnq=1/(2*dt);          % calc maximum frequency
T=N*dt;                % calc period of waveshape
df=1/T;                % calc frequency resolution
fq=-Fnq+[0:(N-1)]'*df +df/2;   % create frequency vector for plot
mag=abs(h);
plot(fq,mag,'d'); ylabel('iF filtered FFT magnitude using zero phase filtering (final filter)');
xlabel('frequency')
axis([-80 80 0 inf])
figure;


%time data
plot(t(1:N), real(iflfiltered)) ;  ylabel('iF filtered time data with zero phase filtering'); xlabel('time')
figure;

ifl_filteredFFT_zerofrcomp=real(mean(iflfiltered));


%Up to here for filtering of field quantities.
%*********************************************************************
```

%Put the filtered VF, iF back to their original vectors
%Moreover, correct for any possible reduction in the amplitude of the signal because of the %filtering

clear vfl ifl %because they contain the original data, now they will contain the filtered

vfl=vflfiltered*(vfl_unfilteredFFT_zerofrcomp/vfl_filteredFFT_zerofrcomp);
ifl=iflfiltered*(ifl_unfilteredFFT_zerofrcomp/ifl_filteredFFT_zerofrcomp);

% Vfl and Ifl are written to the phase data matrices
vabc(1:nt,4)=vfl; %the field quantities are stored in the 4th column in the vabc and iabc matrices
iabc(1:nt,4)=ifl;

% impedance/phase
r=0.003; %stator per phase resistance
xq=1.865; %per phase direct axis impedance

% Delta calculation and phase-neutral conversion of the voltages
for (e=1:nt)
  P(e,1)=(vabc(e,1)*iabc(e,1)-vabc(e,2)*iabc(e,3))/(3*mvab); %per phase active power in p.u.
  Q(e,1)=(vabc(e,1)*iabc(e,3)+vabc(e,2)*iabc(e,1)+vabc(e,3)*iabc(e,2))/(sqrt(3)*3*mvab);
                                                        %per phase reactive power in p.u.
end;
thetapq(1:nt,1)=atan2(Q,P); %power factor angle (atan2 takes into account all possible quadrants)

%The block below calculates the angle between the voltages of two phases taking into
%account the different quadrants and a possibility of "divide by zero" problem
%Note:
%The angle is calculated using the following equation
%thetavabc(i,j)=atan(-diff. of two voltage/(sqrt(3)*sum of two voltages))
%the tolerance for avoiding the "divide by zero problem is taken to be 1e-6.

for (e=1:nt) %for "nt" number of data points
  for (j=1:3) %for 3 phases
    phase1=next(j); %gets the next phase in the phase sequence A-B-C-A.....
    phase2=next(phase1);
    if (vabc(e,phase1)+vabc(e,phase2)>0) %sum of voltages greater than zero
      if (abs(-sqrt(3)*(vabc(e,phase1)+vabc(e,phase2)))>1e-6) %sum far greater than zero
        thetavabc(e,j)=pi+(atan((vabc(e,phase1)-vabc(e,phase2))/(-sqrt(3)*(vabc(e,phase1)+
                              abc(e,phase2))))) ; %the angle lies in the second quadrant
      else
        thetavabc(e,j)=pi+sign(vabc(e,phase1)-vabc(e,phase2))*pi/2; %sum close to zero
      end;
    elseif (vabc(e,phase1)-vabc(e,phase2)<0) %difference of voltages less than zero
      if (abs(-sqrt(3)*(vabc(e,phase1)+vabc(e,phase2)))>1e-6)
                                              %sum of the voltages greater than zero
        thetavabc(e,j)=2*pi+(atan((vabc(e,phase1)-vabc(e,phase2))/(-sqrt(3)*(vabc(e,phase1)+
                              vabc(e,phase2))))); %angle lies in the 3rd quadrant
      else
        thetavabc(e,j)=2*pi+sign(vabc(e,phase1)-vabc(e,phase2))*pi/2;
                        %divide by zero is taken care of along with the third quadrant

```
        end;
      else
        if (abs(-sqrt(3)*(vabc(e,phase1)+vabc(e,phase2)))>1e-6)
                                              %the remaining: the first quadrant!!
thetavabc(e,j)=(atan((vabc(e,phase1)-vabc(e,phase2))
                                      /(-sqrt(3)* (vabc(e,phase1)+vabc(e,phase2)))));
        else
          thetavabc(e,j)=sign(vabc(e,phase1)-vabc(e,phase2))*pi/2; %divide by zero problem again!
        end;
      end;
    end;
end;
%End of calculation of the angle between two phases




%Calculate the instantaneous phase-neutral rms voltage
for (e=1:nt)
  for (j=1:3)
    phase1=next(j);
    phase2=next(phase1);
    vtrms(e,j)=(-(vabc(e,phase1)+vabc(e,phase2))/(cos(thetavabc(e,j)))/(sqrt(2)*kvb*sqrt(3)));
  end;
end;

for (e=1:nt)
  for (j=1:3)
    vabc(e,j)=vtrms(e,j)*sqrt(2)*kvb*cos(thetavabc(e,j)-pi/6);
  end;
end;
%End of conversion of voltage from line-line to phase-neutral voltage


%Similar calculations are performed for getting the angle currents of the two phases.
%The calculations are performed only for phase A.
for (e=1:nt)
  phase1=2;
  phase2=3;
 if (iabc(e,phase1)+iabc(e,phase2)>0)
    if (abs(-sqrt(3)*(iabc(e,phase1)+iabc(e,phase2)))>1e-6)
      thetaia(e,1)=pi+(atan((iabc(e,phase1)-iabc(e,phase2))
                                              /(-sqrt(3)*(iabc(e,phase1)+iabc(e,phase2)))));
    else
      thetaia(e,1)=pi+sign(iabc(e,phase1)-iabc(e,phase2))*pi/2;
    end;
  elseif (iabc(e,phase1)-iabc(e,phase2)<0)
    if (abs(-sqrt(3)*(iabc(e,phase1)+iabc(e,phase2)))>1e-6)
      thetaia(e,1)=2*pi+(atan((iabc(e,phase1)-iabc(e,phase2))
                                              /(-sqrt(3)*(iabc(e,phase1)+iabc(e,phase2)))));
    else
      thetaia(e,1)=2*pi+sign(iabc(e,phase1)-iabc(e,phase2))*pi/2;
    end;
```

```
    else
      if (abs(-sqrt(3)*(iabc(e,phase1)+iabc(e,phase2)))>1e-6)
        thetaia(e,1)=(atan((iabc(e,phase1)-iabc(e,phase2))
                                          /(-sqrt(3)*(iabc(e,phase1)+iabc(e,phase2)))));
      else
        thetaia(e,1)=sign(iabc(e,phase1)-iabc(e,phase2))*pi/2;
      end;
    end;
end;
%End of calculation of angle theta for Phase A


%Calculate the rms current for phase A for each time step
for (e=1:nt)
  phase1=2;
  phase2=3;
  iarms(e,1)=-((iabc(e,phase1)+iabc(e,phase2))/(cos(thetaia(e,1)))/(sqrt(2)*ib));
end;


j=sqrt(-1);

%calculate the instantaneous machine generated emf by the formula
%ef=vt+(r+jxq)*Ia
for (e=1:nt)
  ef(e,1)=vtrms(e,1)+iarms(e,1)*xq*cos(pi/2-thetapq(e,1))+iarms(e,1)*r*cos(-
thetapq(e,1))+j*iarms(e,1)*xq*sin(pi/2-thetapq(e,1))+j*iarms(e,1)*r*sin(-thetapq(e,1));
end;



%delta is the angle between the generated emf phasor and terminal voltage phasor.
delta(1:nt,1)=angle(ef(1:nt));

plot(t,delta*180/pi)
title('delta unfiltered (degrees)')
figure;


%The instantaneous value of delta may contain large spikes which need to be smoothened out.
%The filter below disregards the new value and uses the previous value in the time series if the %two
adjacent values differ by 5 degrees. The value 5 degrees is arbitrary and can be varied to %obtain better
results.

for (e=2:nt)
  if (abs(delta(e)-delta(e-1))>= (5*pi/180))
    delta(e)=delta(e-1);
  end;
end;

plot(t,delta*180/pi)
title('delta filtered (degrees)')
figure;
```

```
deltaunfilteredFFT_zerofrcomp=mean(delta(1:nt));

%Second filter for delta in addition to the one for the spikes.  This is a moving average filter
run=20; %no. of terms in the moving average filter
for (e=run+1:nt)
  delta(e-run)=mean(delta(e-run:e-1));
end;

deltafilteredFFT_zerofrcomp=mean(delta(1:nt-run));

%correct for the filter factor:
delta = delta*(deltaunfilteredFFT_zerofrcomp/deltafilteredFFT_zerofrcomp);

plot(t(1:nt-run),delta(1:nt-run)*180/pi)
title('delta filtered (improved) (degrees)')
figure;


%Since time zero is arbitrary, we need to select when our time reference is located. By definition %at t=0,
the axis a is aligned with the d axis, so Va should be max at time=0
%Search when Va is first maximum
%For this data set, the first maximum occurs at t = 2.8ms (t(29))
%Start using data from vabc(29,:) etc, and make t(29)=0

t=(t*1000-2.8)*1E-3;      %do it this way to avoid round off errors
t(1:28)=[]; %remove first 28 data

vabc(1:28,:)=[];
iabc(1:28,:)=[];
delta(1:28)=[];
thetavabc(1:28)=[];
nt=nt-28;


%convert actual voltage and current data to dq0
parks=zeros(nt*3,3); %A test variable to get the Park's transformation matrix for each time step
for (count=1:nt)
  theta(count)=120*pi*t(count)+delta(count)+pi/2+thetavabc(1,1)-pi/6;
                                                     %theta in the Park's transformation
  tp=zeros(ns,ns); %Park's transformation matrix for individual time step
  tp(1,1:3)=sqrt(1/2); %the first row in the Park's transformation matrix is 1/sqrt(2)

%the cosine terms in the second row of the Park's transformation matrix
  tp(2,1)=cos(theta(count));
  tp(2,2)=cos(theta(count)-(2*pi/3));
  tp(2,3)=cos(theta(count)+(2*pi/3));

%the sine terms in the third row of the Park's transformation matrix
  tp(3,1)=sin(theta(count));
  tp(3,2)=sin(theta(count)-(2*pi/3));
  tp(3,3)=sin(theta(count)+(2*pi/3));

%the rest of the rows contain 1 on the diagonal for damper and field windings
```

```
   for (e=4:ns)
     tp(e,e)=1;
   end;
   tp(1:3,1:3)=tp(1:3,1:3)*sqrt(2/3);
   temp=tp*iabc(count,1:ns)'; %convert the time series current data into dq0 currents
   idq0(count,1:ns)=temp';
   temp=tp*vabc(count,1:ns)'; %convert the time series voltage data into dq0 voltages
   vdq0(count,1:ns)=temp';

%End of Park's transformation.



%Filter dq0 of voltages and currents
%This block filters the variation in the dq0 components of the voltage. The filter below disregards the new
%value and uses the previous value in the time series if the two adjacent values differ by 10%. The figure
%10% is arbitrary and can be varied to obtain better results.
%If any measurement is a spike, then the whole measurement is replaced by its previous.

for (e=2:nt)
   for (j=1:3)
     if (abs((vdq0(e,j)-vdq0(e-1,j))/vdq0(e-1,j))>(0.1))
       vdq0(e,1:3)=vdq0(e-1,1:3);
       idq0(e,1:3)=idq0(e-1,1:3);
   end;
     if (abs((idq0(e,j)-idq0(e-1,j))/idq0(e-1,j))>(0.1))
       vdq0(e,1:3)=vdq0(e-1,1:3);
       idq0(e,1:3)=idq0(e-1,1:3);
   end;
   end;
end;



%Take out the individual 0dq vectors from the 0dq matrices
V0=vdq0(:,1);
Vd=vdq0(:,2);
Vq=vdq0(:,3);
i0=idq0(:,1);
id=idq0(:,2);
iq=idq0(:,3);



%Do Butterworth filters to remove frequency components above 10 Hz (approximately)
N=nt;
%Find order and normalized frequency using the buttord function
fN=1/(2*dt); %Nyquist frequency
fc=5; %cutoff frequency
fstop=200;% frequency where stopband begins

Wp=fc/fN; %passband corner frequency
Ws=fstop/fN; %stopband corner frequency
Rp=0.001; %passband ripple in dB (max permissible passband loss in dB)
Rs=80; %stopband attenuation in dB (number of dB the stopband is down from the passband)
```

```
[n, Wn]=buttord(Wp, Ws, Rp, Rs);
[b,a]=butter(n, Wn); %order and normalized cutoff frequency


V0filtered=filtfilt(b,a,V0);
Vdfiltered=filtfilt(b,a,Vd);
Vqfiltered=filtfilt(b,a,Vq);
i0filtered=filtfilt(b,a,i0);
idfiltered=filtfilt(b,a,id);
iqfiltered=filtfilt(b,a,iq);


%re-filter
for y=1:200
    V0filtered=filtfilt(b,a,V0filtered);
    Vdfiltered=filtfilt(b,a,Vdfiltered);
    Vqfiltered=filtfilt(b,a,Vqfiltered);
    i0filtered=filtfilt(b,a,i0filtered);
    idfiltered=filtfilt(b,a,idfiltered);
    iqfiltered=filtfilt(b,a,iqfiltered);
    y=y+1;
end


%put signals back into the 0dq matrix

vdq0(1:N,1)=V0filtered;
vdq0(1:N,2)=Vdfiltered;
vdq0(1:N,3)=Vqfiltered;
idq0(1:N,1)=i0filtered;
idq0(1:N,2)=idfiltered;
idq0(1:N,3)=iqfiltered;



% convert current dq0 data in per unit
idq0pu(:,1:3)=idq0(:,1:3)/ib;
idq0pu(:,4:ns)=idq0(:,4:ns)/cfb;



% convert voltage dq0 data in per unit
vdq0pu(:,1:3)=vdq0(:,1:3)/kvb;
vdq0pu(:,4:ns)=vdq0(:,4:ns)/vfb;

%End of perunitization
```

%Calculate generator parameters

S3r = 213.7;   %three phase rated power in MVA
Vr = 18;
fr = 60;
IFrated = 545.4545455;

xd = 1.954;
xdprime = 0.295;
xddoubleprime = 0.209;

xq = 1.865;
xqprime = 0.469;
xqdoubleprime = 0.201;

xld = 0.173;
R1 = 0.003;
x0 = 0.128;
TDP0 = 4.767;
TDPP0 =0.033;
TQP0 = 0.396
TQPP0 = 0.073;

%call function to calculate bases and parameters
[Sbase, Vbase, Ibase, Rbase, VFbase, IFbase, RFbase, r, rn, rF, rD, rG, rQ, L0, Ln, Ld, Lq,...
LAD, LAQ, MX, kMF, kMD, LF, LD, MY, kMG, kMQ, LG, LQ, xld, xlq, xlF, xlD, xlG, xlQ] =
param_calculation(S3r, Vr, fr, IFrated, xd, xdprime, xddoubleprime, xq, xqprime, …
        xqdoubleprime, xld, R1, x0, TDP0, TDPP0, TQP0, TQPP0);

w=1; %p.u.
wbase = 2*pi*fr; %base frequency in rad/s

rows=N; %use up to the data that we filtered before

ipu=real(idq0pu(1:N,:)); %to agree with the notation below
V=real(vdq0pu(1:N,:));
deltat=t(2)-t(1);

%Now let's find the current derivatives
for e=1:(rows-1)
iprime(e, 1:4) = (ipu(e+1, 1:4)-ipu(e, 1:4))/deltat;
end;

%Do observer for Model 2.2x
%Our observer equations are of the form
%iD(n+1) = a1*iD(n) + a2*(idprime(n)+iFprime(n)
%iG(n+1) = a3*iG(n) + a4*iQ(n) + a5*iqprime(n)
%iQ(n+1) = a6*iQ(n) + a7*iG(n) + a8*iqprime(n)

```
%First assign the constants to avoid repeating the same calculations
a1 = 1 - wbase*rD*deltat/(xlD+LAD);
a2 = -LAD*deltat/(xlD+LAD);
den = (LAQ+xlQ)*(LAQ+xlG)-LAQ^2;
a3 = 1 - rG*wbase*deltat*(LAQ+xlQ)/den;
a4 = LAQ*rQ*wbase*deltat/den;
a5 = (LAQ*deltat/(LAQ+xlG))*(LAQ*xlG/den - 1);
a6 = 1 - rQ*wbase*deltat*(LAQ+xlG)/den;
a7 = LAQ*rG*wbase*deltat/den;
a8 = -LAQ*deltat*xlG/den;


%Initial conditions:
iD(1,1)=0;
iG(1,1)=0;
iQ(1,1)=0;


%Now calculate the damper currents:
for e = 1:rows-2
   iD(e+1,1) = a1*iD(e,1) + a2*(iprime(e,2)+iprime(e,4));
   iG(e+1,1) = a3*iG(e,1) + a4*iQ(e,1) + a5*iprime(e,3);
   iQ(e+1,1) = a6*iQ(e,1) + a7*iG(e,1) + a8*iprime(e,3);
end


%Plot damper currents
plot(t(1:rows-1),iD,t(1:rows-1),iG,':',t(1:rows-1),iQ,'.' )
title('estimated i_D, i_G and i_Q')
legend('i_D', 'i_G', 'i_Q')
figure;


%Find derivatives for iD, iG and iQ:
for e=1:(rows-3)
  iDprime(e,1) = (iD(e+1,1)-iD(e,1))/deltat;
  iGprime(e,1) = (iG(e+1,1)-iG(e,1))/deltat;
  iQprime(e,1) = (iQ(e+1,1)-iQ(e,1))/deltat;
end;


%IMPLEMENTATION OF SATURATION
%First, calculate saturation constants AGSAT and BGSAT in the following expression
%    SG = AGSAT*exp(BGSAT*(VT - V0));
%Saturation constants are specific to the generator

IA = IFrated;
IB = 577;          %Note this as AFNL in GUI
IC = 820;


Sg1 = (IB-IA)/IB;
Sg2 = (IC-1.2*IA)/(1.2*IA);
```

```
BGSAT = -5*log(Sg1/Sg2);
AGSAT = (Sg1^2)/Sg2;


lamdaad(:,1) = V(:,3) + r*ipu(:,3) + xld*ipu(:,2);
lamdaaq(:,1) = -V(:,2) - r*ipu(:,2) + xld*ipu(:,3);


lamdaat=(sqrt((mean(lamdaad))^2+(mean(lamdaaq))^2))/sqrt(3);
                %The sqrt(3) is to correct for the different  base in the open circuit characteristic


%Calculate saturation effect in d-axis (lamdaId)

lamdaId = AGSAT*exp(BGSAT*(lamdaat-0.82));

Ksd = lamdaat/(lamdaat+lamdaId);


%for lack of q-axis data assume saturation is the same in both axes
Ksq=Ksd;

%Correct inductances for saturation
LADs=LAD*Ksd;
LAQs=LAQ*Ksq;

%End of saturation calculations

%Make rows=rows-1 for simplicity
rows=rows-1;


disp('Estimation of parameters for Model 2.2x with saturation included')

%Estimate LAD
j=1;

for e=2000:(rows-20)
   H(j,:)=[(1/wbase)*(iprime(e,2)+iprime(e,4)+iDprime(e,1))];
   H(j+1,:)=[-w*(ipu(e,2)+ipu(e,4)+iD(e,1))];
   H(j+2,:)=[(1/wbase)*(iprime(e,2)+iprime(e,4)+iDprime(e,1))];

   Z(j,1)=-V(e,2)-r*ipu(e,2)-w*(LAQs+xlq)*ipu(e,3)-w*LAQs*iG(e,1)-w*LAQs*iQ(e,1)-
                                              (1/wbase)*xld*iprime(e,2);
   Z(j+1,1)=-V(e,3)+w*xld*ipu(e,2)-r*ipu(e,3)-(1/wbase)*((LAQs+xlq)*iprime(e,3)+
                                         LAQs*iGprime(e,1)+ LAQs*iQprime(e,1));
   Z(j+2,1)=-V(e,4)-rF*ipu(e,4)-(1/wbase)*xlF*iprime(e,4);
   j=j+3;
end

x=pinv(H)*Z

clear H Z x
```

```
%Estimate LAQ
j=1;

for e=2000:(rows-20)
   H(j,:)=[w*(ipu(e,3)+iG(e,1)+iQ(e,1))];
   H(j+1,:)=[(1/wbase)*(iprime(e,3)+iGprime(e,1)+iQprime(e,1))];
   H(j+2,:)=[0];

   Z(j,1)=-V(e,2)-r*ipu(e,2)-w*xlq*ipu(e,3)-(1/wbase)*((LADs+xld)*iprime(e,2)+
                                              LADs*iprime(e,4) + LADs*iDprime(e,1));
   Z(j+1,1)=-V(e,3)+w*(LADs+xld)*ipu(e,2)-r*ipu(e,3)+w*LADs*ipu(e,4)+w*LADs*iD(e,1)-
                                              (1/wbase)*xlq*iprime(e,3);
   Z(j+2,1)=-V(e,4)-rF*ipu(e,4)-(1/wbase)*(LADs*iprime(e,2)+(LADs+xlF)*iprime(e,4)+
                                              LADs*iDprime(e,1));

   j=j+3;
end

x=pinv(H)*Z

clear H Z x


%Estimate LAD, LAQ
j=1;

for e=2000:(rows-20)
   H(j,:)=[(1/wbase)*(iprime(e,2)+iprime(e,4)+iDprime(e,1)), w*(ipu(e,3)+iG(e,1)+iQ(e,1))];
   H(j+1,:)=[-w*(ipu(e,2)+ipu(e,4)+iD(e,1)), (1/wbase)*(iprime(e,3)+iGprime(e,1)+
                                              iQprime(e,1))];
   H(j+2,:)=[(1/wbase)*(iprime(e,2)+iprime(e,4)+iDprime(e,1)), 0];

   Z(j,1)=-V(e,2)-r*ipu(e,2)-w*xlq*ipu(e,3)-(1/wbase)*xld*iprime(e,2);
   Z(j+1,1)=-V(e,3)+w*xld*ipu(e,2)-r*ipu(e,3)-(1/wbase)*xlq*iprime(e,3);
   Z(j+2,1)=-V(e,4)-rF*ipu(e,4)-(1/wbase)*xlF*iprime(e,4);
   j=j+3;
end

x=pinv(H)*Z

clear H Z x


%Estimate rF
j=1;

for e=2000:(rows-20)
   H(j,:)=[0];
   H(j+1,:)=[0];
   H(j+2,:)=[ipu(e,4)];

   Z(j,1)=-V(e,2)-r*ipu(e,2)-w*(LAQs+xlq)*ipu(e,3)-w*LAQs*iG(e,1)-w*LAQs*iQ(e,1)-
          (1/wbase)*((LADs+xld)*iprime(e,2)+LADs*iprime(e,4)+LADs*iDprime(e,1));
   Z(j+1,1)=-V(e,3)+w*(LADs+xld)*ipu(e,2)-r*ipu(e,3)+w*LADs*ipu(e,4)+w*LADs*iD(e,1)-
```

```
                (1/wbase)*((LAQs+xlq)*iprime(e,3)+LAQs*iGprime(e,1)+LAQs*iQprime(e,1));
     Z(j+2,1)=-V(e,4)-(1/wbase)*(LADs*iprime(e,2)+(LADs+xlF)*iprime(e,4) +
                                                    LADs*iDprime(e,1));

     j=j+3;
end

x=pinv(H)*Z

clear H Z x


%Estimate r
j=1;

for e=2000:(rows-20)
   H(j,:)=[ipu(e,2)];
   H(j+1,:)=[ipu(e,3)];
   H(j+2,:)=[0];

   Z(j,1)=-V(e,2)-w*(LAQs+xlq)*ipu(e,3)-w*LAQs*iG(e,1)-w*LAQs*iQ(e,1)-
          (1/wbase)*((LADs+xld)*iprime(e,2)+LADs*iprime(e,4)+LADs*iDprime(e,1));
   Z(j+1,1)=-V(e,3)+w*(LADs+xld)*ipu(e,2)+w*LADs*ipu(e,4)+w*LADs*iD(e,1)-
             (1/wbase)*((LAQs+xlq)*iprime(e,3)+LAQs*iGprime(e,1)+LAQs*iQprime(e,1));
   Z(j+2,1)=-V(e,4)-rF*ipu(e,4)-(1/wbase)*(LADs*iprime(e,2)+(LADs+xlF)*iprime(e,4)+
                                                    LADs*iDprime(e,1));

   j=j+3;
end

x=pinv(H)*Z

clear H Z x


%Estimate LAD, LAQ, rF
j=1;

for e=2000:(rows-20)
   H(j,:)=[(1/wbase)*(iprime(e,2)+iprime(e,4)+iDprime(e,1)), w*(ipu(e,3)+iG(e,1)+iQ(e,1)), 0];
   H(j+1,:)=[-w*(ipu(e,2)+ipu(e,4)+iD(e,1)), (1/wbase)*(iprime(e,3)+iGprime(e,1)+
                                                    iQprime(e,1)), 0];
   H(j+2,:)=[(1/wbase)*(iprime(e,2)+iprime(e,4)+iDprime(e,1)), 0, ipu(e,4)];

   Z(j,1)=-V(e,2)-r*ipu(e,2)-w*xlq*ipu(e,3)-(1/wbase)*xld*iprime(e,2);
   Z(j+1,1)=-V(e,3)+w*xld*ipu(e,2)-r*ipu(e,3)-(1/wbase)*xlq*iprime(e,3);
   Z(j+2,1)=-V(e,4)-(1/wbase)*xlF*iprime(e,4);
   j=j+3;
end

x=pinv(H)*Z

clear H Z x
```

APPENDIX H

VISUAL C++ CODE FOR PARAMETER ESTIMATION AND GUI

IMPLEMENTATION USING ACTUAL MEASUREMENTS

```
/////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
//Portion of graphic user interface implementation file                                                     //
//Constructs a user friendly Windows based dialog system to read input data files and known                 //
//data to estimate the user selected synchronous generator parameters                                       //
//Copyright: Elias Kyriakides                                                                                //
/////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////

// CDialog1Dlg.cpp : implementation file
//
#include "stdafx.h"
#include "Estimator.h"
#include "CDialog1Dlg.h"
#include <iostream>
#include <fstream>
#include <vector>
#include <iomanip>
#include <math.h>
#include <stdlib.h>
#include "Dialog2Dlg.h"
#include <stdio.h>
#include <string>

#include "LinAlg.h"              //To allow use of the linear algebra package in this file
#include "LAStreams.h"   //To allow use of streams of the linear algebra package
#include "svd.h"              //To allow use of the singular value decomposition capabilities
                                             //of the linear algebra package

using namespace std;

#ifdef _DEBUG
#define new DEBUG_NEW
#undef THIS_FILE
static char THIS_FILE[] = __FILE__;
#endif

#undef min      //To make LinAlg compatible with MFC
#undef max


double X[16][2]; //X is the matrix containing the estimated parameters
                     //Initialized it here to access it from all functions (global)
                     //The first column contains the value of the estimated parameter
                     //The second column is 1 if that parameter was estimated and zero otherwise.
                     //X[15][0] contains the rms error of the estimation
```

```
/////////////////////////////////////////////////////////////////////
// CDialog1Dlg dialog

CDialog1Dlg::CDialog1Dlg(CWnd* pParent /*=NULL*/)
        : CDialog(CDialog1Dlg::IDD, pParent)
{
        //{{AFX_DATA_INIT(CDialog1Dlg)
        m_filename = _T("");
        m_rF = FALSE;
        m_r = FALSE;
        m_r3rn = FALSE;
        m_Lq = FALSE;
        m_Ld = FALSE;
        m_MF = FALSE;
        m_MD = FALSE;
        m_L03Ln = FALSE;
        m_LDdamper = FALSE;
        m_LF = FALSE;
        m_MR = FALSE;
        m_rD = FALSE;
        m_Comtradedata = 0;    //causes the Comtrade data radio button to be selected at startup
        m_L2method = 0;        //causes the L2 estimation method radio button to be selected at startup
        m_frequency = 60.0;
        m_Ifield_airgap = 1226.0;
        m_xLm = 0.160;
        m_S3Base = 483.0;
        m_V3Base = 22.0;
        m_R1 = 0.0046;
        m_x0 = 0.150;
        m_xd = 1.80;
        m_xq = 1.72;
        m_Ln = 100.0;
        m_rn = 100.0;
        m_taudoubleprimed = 0.032;
        m_taudoubleprimeqzero = 0.059;
        m_tauprimedzero = 3.7;
        m_xdoubleprimedv = 0.190;
        m_xdoubleprimeqv = 0.190;
        m_xprimedv = 0.270;
        m_EnableWeights=0;       //causes the Enable Weights button to be selected at startup
        m_FullFilter = 0; //causes the Full Filter button to be selected at startup
        m_rQ = FALSE;
        m_LQdamper = FALSE;
        m_MQ = FALSE;
        //}}AFX_DATA_INIT
}
void CDialog1Dlg::DoDataExchange(CDataExchange* pDX)
{
        CDialog::DoDataExchange(pDX);
        //{{AFX_DATA_MAP(CDialog1Dlg)
        DDX_Text(pDX, IDC_FILENAME, m_filename);
        DDX_Check(pDX, IDC_rF, m_rF);
```

```
        DDX_Check(pDX, IDC_r, m_r);
        DDX_Check(pDX, IDC_r3rn, m_r3rn);
        DDX_Check(pDX, IDC_Lq, m_Lq);
        DDX_Check(pDX, IDC_Ld, m_Ld);
        DDX_Check(pDX, IDC_MF, m_MF);
        DDX_Check(pDX, IDC_MD, m_MD);
        DDX_Check(pDX, IDC_L03Ln, m_L03Ln);
        DDX_Check(pDX, IDC_LDdamper, m_LDdamper);
        DDX_Check(pDX, IDC_LF, m_LF);
        DDX_Check(pDX, IDC_MR, m_MR);
        DDX_Check(pDX, IDC_rD, m_rD);
        DDX_Radio(pDX, IDC_Comtradedata, m_Comtradedata);
        DDX_Radio(pDX, IDC_L2method, m_L2method);
        DDX_Text(pDX, IDC_frequency, m_frequency);
        DDX_Text(pDX, IDC_Ifield_airgap, m_Ifield_airgap);
        DDX_Text(pDX, IDC_xLm, m_xLm);
        DDX_Text(pDX, IDC_S3Base, m_S3Base);
        DDX_Text(pDX, IDC_V3Base, m_V3Base);
        DDX_Text(pDX, IDC_R1, m_R1);
        DDX_Text(pDX, IDC_x0, m_x0);
        DDX_Text(pDX, IDC_xd, m_xd);
        DDX_Text(pDX, IDC_xq, m_xq);
        DDX_Text(pDX, IDC_Ln, m_Ln);
        DDX_Text(pDX, IDC_rn, m_rn);
        DDX_Text(pDX, IDC_taudoubleprimed, m_taudoubleprimed);
        DDX_Text(pDX, IDC_taudoubleprimeqzero, m_taudoubleprimeqzero);
        DDX_Text(pDX, IDC_tauprimedzero, m_tauprimedzero);
        DDX_Text(pDX, IDC_xdoubleprimedv, m_xdoubleprimedv);
        DDX_Text(pDX, IDC_xdoubleprimeqv, m_xdoubleprimeqv);
        DDX_Text(pDX, IDC_xprimedv, m_xprimedv);
        DDX_Radio(pDX, IDC_EnableWeights, m_EnableWeights);
        DDX_Radio(pDX, IDC_FullFilter, m_FullFilter);
        DDX_Check(pDX, IDC_rQ, m_rQ);
        DDX_Check(pDX, IDC_LQdamper, m_LQdamper);
        DDX_Check(pDX, IDC_MQ, m_MQ);
        //}}AFX_DATA_MAP
        UpdateOKUI();              //Disables "Start Estimator" button at startup when empty
}

BEGIN_MESSAGE_MAP(CDialog1Dlg, CDialog)
        //{{AFX_MSG_MAP(CDialog1Dlg)
        ON_BN_CLICKED(IDC_BROWSE, OnBrowse)
        ON_EN_CHANGE(IDC_FILENAME, OnChangeFilename)
        ON_BN_CLICKED(IDC_rF, OnrF)
        ON_BN_CLICKED(IDC_r, Onr)
        ON_BN_CLICKED(IDC_r3rn, Onr3rn)
        ON_BN_CLICKED(IDC_Lq, OnLq)
        ON_BN_CLICKED(IDC_Ld, OnLd)
        ON_BN_CLICKED(IDC_MF, OnMF)
        ON_BN_CLICKED(IDC_MD, OnMD)
        ON_BN_CLICKED(IDC_rD, OnrD)
        ON_BN_CLICKED(IDC_L03Ln, OnL03Ln)
```

```
                ON_BN_CLICKED(IDC_LF, OnLF)
                ON_BN_CLICKED(IDC_MR, OnMR)
                ON_BN_CLICKED(IDC_LDdamper, OnLDdamper)
                ON_BN_CLICKED(IDC_HelpButton1, OnHelpButton1)
                ON_BN_CLICKED(IDC_HelpButton2, OnHelpButton2)
                ON_BN_CLICKED(IDC_HelpButton3, OnHelpButton3)
                ON_BN_CLICKED(IDC_HelpButton4, OnHelpButton4)
                ON_BN_CLICKED(IDC_rQ, OnrQ)
                ON_BN_CLICKED(IDC_LQdamper, OnLQdamper)
                ON_BN_CLICKED(IDC_MQ, OnMQ)
                ON_EN_KILLFOCUS(IDC_S3Base, OnKillfocusS3Base)
                ON_EN_KILLFOCUS(IDC_V3Base, OnKillfocusV3Base)
                ON_EN_KILLFOCUS(IDC_Ifield_airgap, OnKillfocusIfieldairgap)
                ON_EN_KILLFOCUS(IDC_frequency, OnKillfocusfrequency)
                ON_EN_KILLFOCUS(IDC_rn, OnKillfocusrn)
                ON_EN_KILLFOCUS(IDC_Ln, OnKillfocusLn)
                ON_EN_KILLFOCUS(IDC_xd, OnKillfocusxd)
                ON_EN_KILLFOCUS(IDC_xq, OnKillfocusxq)
                ON_EN_KILLFOCUS(IDC_xprimedv, OnKillfocusxprimedv)
                ON_EN_KILLFOCUS(IDC_xdoubleprimedv, OnKillfocusxdoubleprimedv)
                ON_EN_KILLFOCUS(IDC_xdoubleprimeqv, OnKillfocusxdoubleprimeqv)
                ON_EN_KILLFOCUS(IDC_x0, OnKillfocusx0)
                ON_EN_KILLFOCUS(IDC_xLm, OnKillfocusxLm)
                ON_EN_KILLFOCUS(IDC_R1, OnKillfocusR1)
                ON_EN_KILLFOCUS(IDC_tauprimedzero, OnKillfocustauprimedzero)
                ON_EN_KILLFOCUS(IDC_taudoubleprimed, OnKillfocustaudoubleprimed)
                ON_EN_KILLFOCUS(IDC_taudoubleprimeqzero, OnKillfocustaudoubleprimeqzero)
                //}}AFX_MSG_MAP
END_MESSAGE_MAP()


/////////////////////////////////////////////////////////////////////
// CDialog1Dlg message handlers

void CDialog1Dlg::OnBrowse()
{
        CFileDialog dlg(
                true,
                NULL,
                NULL,
                OFN_HIDEREADONLY,
                _T("Text files (.txt)|*.txt|")
                _T("Data files (.dat)|*.dat|")
                _T("IEEE Comtrade files (.cfg; .dat)|*.cfg; *.dat|")
                _T("|")
                );
        if (IDOK!=dlg.DoModal())
                return;
        m_FileNameFull = dlg.GetPathName();
        UpdateData(false);
        UpdateOKUI();        //Disables "Start Estimator" button when it is emptied
}
```

```
void CDialog1Dlg::OnOK()
{
        extern double X[16][2];    //X is the matrix containing the estimated parameters
        mainprogram();             //Calls the function mainprogram.
                                   //When this process ends, the estimator finishes.

        CDialog::OnOK();

        MessageBox("The Estimator has finished.", "Simulation Finished", MB_OK |
MB_ICONINFORMATION);
        CDialog2Dlg dlg2;                          //Declares the output dialog


//Presentation of results:
CString
Y[15]={"r+3*rn","r","Lq","Ld","MF","MD","rF","rD","L0+3*Ln","LF","MR","LD","rQ","LQ","MQ"};
                            //String matrix containing the names of the estimated parameters
int e=0;
for (int i=0; i<15; i++)
{
        if (X[i][1]==1)
        {       dlg2.m_param1 = Y[i];
                dlg2.m_out1 = X[i][0];
                e=i;
                i=15;//to force break of the for loop since an estimated parameter was detected
        }
}

if (e==14) goto PointA;

for (i=e+1; i<15; i++)
{ if (X[i][1]==1)
        {       dlg2.m_param2 = Y[i];
                dlg2.m_out2 = X[i][0];
                e=i;
                i=15;}
}

if (e==14) goto PointA;

for (i=e+1; i<15; i++)
{ if (X[i][1]==1)
        {       dlg2.m_param3 = Y[i];
                dlg2.m_out3 = X[i][0];
                e=i;
                i=15;}
}

if (e==14) goto PointA;

for (i=e+1; i<15; i++)
{ if (X[i][1]==1)
```

```
              {          dlg2.m_param4 = Y[i];
                         dlg2.m_out4 = X[i][0];
                         e=i;
                         i=15;}
}

if (e==14) goto PointA;

for (i=e+1; i<15; i++)
{ if (X[i][1]==1)
              {          dlg2.m_param5 = Y[i];
                         dlg2.m_out5 = X[i][0];
                         e=i;
                         i=15;}
}

dlg2.m_error = X[15][0];    //outputs the rms error of the estimation
PointA:  if (IDOK == dlg2.DoModal())                  //implements the output dialog
                    {}
}


void CDialog1Dlg::OnCancel()
{
        MessageBox("This will cancel the estimation.", "Exit the Estimator", MB_OK |
MB_ICONINFORMATION);
        CDialog::OnCancel();
        CDialog::OnOK();
}


void CDialog1Dlg::UpdateOKUI()
{
        CString strFileName;
        GetDlgItemText(IDC_FILENAME, strFileName);
        GetDlgItem(IDOK)->EnableWindow(strFileName!=_T(""));
}


void CDialog1Dlg::OnChangeFilename()
{
        CString strFileName;

   CEdit *pEdit = (CEdit *)GetDlgItem(IDC_FILENAME); // Get the edit control named
IDC_FILENAME
   ASSERT_VALID(pEdit);

   CButton *pBtnOK = (CButton *)GetDlgItem(IDOK); // Get the OK button
        ASSERT_VALID(pBtnOK);
   pEdit->GetWindowText(strFileName); // get the text from the control into strFileName

   if ( strFileName.IsEmpty() )
```

```
        pBtnOK->EnableWindow(FALSE);
    else
        pBtnOK->EnableWindow(TRUE);
}


void CDialog1Dlg::mainprogram()
{
//////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
// This file reads the data supplied in the input file and stores the data into columns. It then
// arranges the data in the form Hx=Z (with the help of the Linear Algebra package), and
// estimates  the parameters required  by the user.
//////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////

//Last modified on December 11, 2002

//Check state of "file" radio buttons to select the data format
        int radioState_Comtrade;            //It will be assigned to 0 or 1 depending on state of button
        CButton* pRadio_Comtrade = (CButton*)GetDlgItem(IDC_Comtradedata);
        radioState_Comtrade = pRadio_Comtrade->GetCheck();

        int radioState_abc=0;
                //not really needed? see  if else statement below
        CButton* pRadio_abc = (CButton*)GetDlgItem(IDC_abcdata);
        radioState_abc = pRadio_abc->GetCheck();


//Depending on the selection of the data format, the program will now divide into two sections
//These nine vectors are used to store the measurements from the selected data file

        vector<double> t, IA, IB, IC, VF, VAB, VBC, VCA, IF;
        double a1, a2, a3, a4, a5, a6, a7, a8, a9;

        if (radioState_Comtrade==1)  //If the user selects the option to read a Comtrade data file:
        {
                //read .cfg file first

                CString strFile1 = m_FileNameFull;  //procedure to get name of .cfg file
                CString strFile2 = strFile1;                    //we have read the .dat file (strFile1)
                strFile2=m_FileNameFull;
                strFile2.Replace(".dat", ".cfg");

                char heading[3];
                int channels;
                char dum1[6];
                int ch1;            //holds channel numbers
                char dum2[3];
                char dum3[2];       //dum3, 4 compose the channel identifier
                char dum4[2];
                char dum5[8];       //channel phase identification and units
                char dum6;          //the comma after the unit
                float at;           //channel multiplier
```

```
            float bt;           //channel offset
            float skew;         //time skew
            float minpo;        //minimum possible data value
            float maxpo;        //maximum possible data value
            int qp;             //VT or CT ratio primary
            int qs;             //VT or CT ratio secondary
            char q1;            //primary or secondary data sealing identifier
            int freq;           //frequency
            int samplingrates;  //number of sampling rates
            float samplerate;   //sample rate in Hz
            int lastno;         //last sample number
            char date1[26]      //start date and time
            char date2[26]      //end date and time
            char datatype[10];  //Data file type, e.g. ASCII
            float timemult;     //Time stamp multiplication factor
            vector<int> ch;
            vector<double> a, b;
            ifstream cfgfile;
            cfgfile.open(strFile2);
//Read the first two informatory lines
            cfgfile >> heading;
            cfgfile >> channels;
            cfgfile >> dum1;
//Read all channels (each channel the characteristics of one variable)
            for (int k=0; k<channels; k++)
            {
                    cfgfile >> ch1;
                    cfgfile >> dum2;
                    cfgfile >> dum3;
                    cfgfile >> dum4;
                    cfgfile >> dum5;
                    cfgfile >> dum6;
                    cfgfile >> at;
                    cfgfile >> dum6;
                    cfgfile >> bt;
                    cfgfile >> dum6;
                    cfgfile >> skew;
                    cfgfile >> dum6;
                    cfgfile >> minpo;
                    cfgfile >> dum6;
                    cfgfile >> maxpo;
                    cfgfile >> dum6;
                    cfgfile >> qp;
                    cfgfile >> dum6;
                    cfgfile >> qs;
                    cfgfile >> dum6;
                    cfgfile >> q1;
                    ch.push_back(ch1);
                    a.push_back(at);
                    b.push_back(bt);
            }
```

```
//Now read the rest of the data in the configuration file
                cfgfile >> freq >> samplingrates >> samplerate >> dum6 >> lastno;
                cfgfile >> date1 >> date2 >> datatype >> timemult;
                cfgfile.close();  //closes the configuration data file


//Now read the .dat file
//Location zero contains the sample number
                char dum7;
                vector<int> measnumber;  //the .dat file has one more column which contains
                int a10;                           /the measurement number.
                ifstream datafile;
                datafile.open(m_FileNameFull);

                for (int q = 0; q<lastno; q++)
                {
                datafile >> a10 >> dum7 >> a1 >> dum7 >> a2 >> dum7 >> a3 >> dum7 >> a4 >> dum7
                >> a5>> dum7 >> a6 >> dum7 >> a7 >> dum7 >> a8 >> dum7 >> a9;

                        measnumber.push_back(a10);                  // append to end of vector and...
                        t.push_back(a1);                            // expand it, if necessary
                        IA.push_back(a2);
                        IB.push_back(a3);
                        IC.push_back(a4);
                        VF.push_back(a5);
                        VAB.push_back(a6);
                        VBC.push_back(a7);
                        VCA.push_back(a8);
                        IF.push_back(a9);
                }
                datafile.close();                                  //closes the .dat data file


//Multiplying factors
                int k1 = t.size();
                for (int j=0; j<k1-1; j++)
                {
                        t[j] = t[j]*(timemult/1E-6);//the time is in microseconds

// To find the correct quantity for each signal we need to multiply the stored signal by its channel
// multiplier a and add any offset b that may exist. These were read from the configuration data  file.
//Further, multiply stator V and I by 1000

                        IA[j]  = 1000*(IA[j] * a[0] + b[0]);
                        IB[j]  = 1000(IB[j] * a[1] + b[1]);
                        IC[j]  = 1000(IC[j] * a[2] + b[2]);
                        VF[j]  = VF[j] * a[3] + b[3];
                        VAB[j] = 1000(VAB[j]* a[4] + b[4]);
                        VBC[j] = 1000(VBC[j]* a[5] + b[5]);
                        VCA[j] = 1000(VCA[j]* a[6] + b[6]);
                        IF[j]  = IF[j] * a[7] + b[7];
```

```
                }
                                                //end of reading Comtrade data files
        }


        if (radioState_abc==1)                          //read a normal abc data file
        {
        ifstream datafile (m_FileNameFull);

        while (datafile >> a1 >> a2 >> a3 >> a4 >> a5 >> a6 >> a7 >> a8 >> a9) //reads data row by row
                {
                        t.push_back(a1);  // append to end of vector and...
                        VAB.push_back(a2);// expand it, if necessary
                        VBC.push_back(a3);
                        VCA.push_back(a4);
                        VF.push_back(a5);
                        IA.push_back(a6);
                        IB.push_back(a7);
                        IC.push_back(a8);
                        IF.push_back(a9);
                }
                datafile.close();                               //closes the data file
        //end of reading abc data
        }



// The following segment calculates the current and voltage bases and all the machine parameters
// that can be calculated from the manufacturer's data.  If some of these are selected to be
// estimated then they are ignored in the estimation process.  If not, then they are used to estimate
// the selected parameters

        //We need to define the constant k and pi
        double   k  = sqrt(3.0/2.0);
        double pi=4*atan(1); //this is one way of calculating pi


        //stator bases
        double SBase=(m_S3Base*1E6)/3.0;
        double VBase=(m_V3Base*1E3)/sqrt(3.0);
        double IBase= SBase/VBase;
        double w=2*pi*m_frequency;
        double LBase=VBase/(w*IBase);

        //parameters I
        double MF=(VBase*sqrt(2))/(w*m_Ifield_airgap);
        double Lmd=(m_xd-m_xLm)*LBase;
        double kMFactual=k*MF;

        //field bases
        double IFBase=IBase/(kMFactual/Lmd);
        double VFBase=SBase/IFBase;
```

```
        double LFBase=pow(kMFactual,2.0)*LBase/pow(Lmd,2.0);
        double MFBase=(kMFactual/Lmd)*LBase;

        //parameters II
        double kMF=kMFactual/MFBase;
        double rn=m_rn;
        double Ln=m_Ln;
        double kMD=kMF;
        double MR=kMF;
        double kMQ=m_xq-m_xLm;
        double Ld=m_xd;
        double Lq=m_xq;
        double L0=m_x0;
        double r=m_R1;

        double LAD=kMF;
        double Lprimed=m_xprimedv;
        double ld=m_xLm;
        double lF=LAD*((Lprimed-ld)/(Ld-Lprimed));
        double LF=lF+LAD;
        double Ldoubleprimed=m_xdoubleprimedv;
        double lD=(LAD*lF*(Ldoubleprimed-ld))/(LAD*lF-lF*(Ldoubleprimed-ld)-
LAD*(Ldoubleprimed-ld));
        double LD=lD+LAD;
        double rD=(Ldoubleprimed*(LD*LF-pow(LAD,2.0)))/(Lprimed*LF*m_taudoubleprimed*w);
        double lq=ld;
        double LAQ=Lq-lq;
        double Ldoubleprimeq=m_xdoubleprimeqv;
        double lQ=LAQ*(Ldoubleprimeq-lq)/(Lq-Ldoubleprimeq);
        double LQ=LAQ+lQ;
        double rQ=LQ/(m_taudoubleprimeqzero*w);
        double rF=LF/(m_tauprimedzero*w);

//end of calculating machine bases and machine parameters *****************************


        int rows = t.size();                    //calculates the # of rows of the vectors and sets it to m

//abc voltages and currents in the data files are in kV and kA. Transform them into V and A
        for (int j=0; j<rows; j++)
        {
                IA[j] *= 1000*0.0026987161;
                IB[j] *= 1000*0.0026987161;
                IC[j] *= 1000*0.0026987161;
                VAB[j]*= 1000*0.0018998961;
                VBC[j]*= 1000*0.0018998961;
                VCA[j]*= 1000*0.0018998961;
                IF[j]*= 0.2072613984;
                VF[j]*= 0.0518153496;
        }
```

```
//then phase quantities are calculated from the line quantities ****************************
//and the torque angle delta is calculated ********************************************


vector<double> P(rows), Q(rows), thetapq(rows);

        for (j=0; j<rows; j++)
        {
        P[j]=(VAB[j]*IA[j]-VBC[j]*IC[j])/(3*SBase);        //per phase active power in pu
        Q[j]=(VAB[j]*IC[j]+VBC[j]*IA[j]+VCA[j]*IB[j])/(sqrt(3)*3*SBase);
                                                        //per phase reactive power in pu
        thetapq[j]=atan2(Q[j],P[j]);
//power factor angle at each measurement (atan2 takes into account all possible quadrants)
        }


// The next for loop calculates the angle between the voltages two phases taking into account the
// different quadrants and a possibility of "divide by zero" problem.  The angle is calculated using
// the equation:
// thetavabc(j,e)=atan(-diff. of two voltages/(sqrt(3)*sum of two voltages)) the tolerance for
// avoiding the divide by zero problem is set to 1e-6.

        vector<double> thetavabc1(rows), thetavabc2(rows), thetavabc3(rows), thetaia(rows);
// 3 vectors containing the angles between the phases of two voltages and a vector containing the
// angle of phase a

//Since we cannot use matrices (do not know their size and do not want to assign arbitrary size),
//use a slightly different algorithm to do the following than the one used in the MATLAB file

        //first phase
        for (j=0; j<rows; j++)
        {
                if (VBC[j]+VCA[j]>0)  //checks if the sum of the voltages is greater than zero

                        if (abs(-sqrt(3.0)*(VBC[j]+VCA[j]))>1E-6) //sum not close to zero

                                thetavabc1[j]=pi+(atan((VBC[j]-VCA[j])/(-
sqrt(3.0)*(VBC[j]+VCA[j])))); //the angle lies in the second quadrant
                        else    //(if sum is close to zero, the angle is going to be either 90 or 270)
                        {
                                int y=CDialog1Dlg::sign(VBC[j],VCA[j]);
                //returns the sign of the difference between the two voltages (+ or -)
                        thetavabc_view(j,e)=pi+y*pi/2;
                        }
                else
                {
                        if (VBC[j]-VCA[j]<0)
                        //checks if the difference of the voltages is less than zero
                                if (abs(-sqrt(3.0)*(VBC[j]-VCA[j]))>1e-6)
                                //sum of the voltages greater than zero
                                        thetavabc1[j]=2*pi+(atan((VBC[j]-VCA[j])/(-
                sqrt(3.0)*(VBC[j]+VCA[j])))); //the angle lies in the third quadrant
                                else   //if sum is close to zero
```

```
                                                 {
                                                         int y=CDialog1Dlg::sign(VBC[j],VCA[j]); //returns
                         the sign of the difference between the two voltages (+ or -)
                                                         thetavabc1[j]=2*pi+y*pi/2;
                                                 }

                                         else
                                                 if (abs(-sqrt(3.0)*(VBC[j]+VCA[j]))>1e-6)   //the
                         remaining case: the first quadrant
                                                         thetavabc1[j]=(atan((VBC[j]-VCA[j])/(-
sqrt(3.0)*(VBC[j]+VCA[j])))); //the angle lies in the first quadrant
                                                 else   //if sum is close to zero
                                                 {
                                                         int y=CDialog1Dlg::sign(VBC[j],VCA[j]);
                         //returns the sign of the difference between the two voltages (+ or -)
                                                         thetavabc1[j]=y*pi/2;
                                                 }
                 }
         }
         //second phase
         for (j=0; j<rows; j++)
         {
                 if (VCA[j]+VAB[j]>0)  //checks if the sum of the voltages is greater than zero
                         if (abs(-sqrt(3.0)*(VCA[j]+VAB[j]))>1E-6) //sum not close to zero
                         thetavabc2[j]=pi+(atan((VCA[j]-VAB[j])/(-sqrt(3.0)*(VCA[j]+VAB[j])))); //the
angle lies in the second quadrant
                         else    //(if sum is close to zero, the angle is going to be either 90 or 270)
                         {
                                 int y=CDialog1Dlg::sign(VCA[j],VAB[j]);
                         //returns the sign of the difference between the two voltages (+ or -)
                         thetavabc_view(j,e)=pi+y*pi/2;
                         }
                 else
                 {
                 if (VCA[j]-VAB[j]<0)
                 //checks if the difference of the voltages is less than zero
                                 if (abs(-sqrt(3.0)*(VCA[j]-VAB[j]))>1e-6)
                                 //sum of the voltages greater than zero
                                         thetavabc2[j]=2*pi+(atan((VCA[j]-VAB[j])/(-
sqrt(3.0)*(VCA[j]+VAB[j])))); //the angle lies in the third quadrant
                                 else   //if sum is close to zero
                                 {
                                         int y=CDialog1Dlg::sign(VCA[j],VAB[j]); //returns
                         the sign of the difference between the two voltages (+ or -)
                                         thetavabc2[j]=2*pi+y*pi/2;
                                 }
                                 else
                                         if (abs(-sqrt(3.0)*(VCA[j]+VAB[j]))>1e-6)   //the
                                         remaining case: the first quadrant
                                                 thetavabc2[j]=(atan((VCA[j]-VAB[j])/(-
sqrt(3.0)*(VCA[j]+VAB[j])))); //the angle lies in the first quadrant
                                         else   //if sum is close to zero
```

```
                                                        {
                                                        int y=CDialog1Dlg::sign(VCA[j],VAB[j]);
                                //returns the sign of the difference between the two voltages (+ or -)
                                                                thetavabc2[j]=y*pi/2;
                                                        }
                        }
                }


        //third phase
        for (j=0; j<rows; j++)
        {
                if (VAB[j]+VBC[j]>0)  //checks if the sum of the voltages is greater than zero
                        if (abs(-sqrt(3.0)*(VAB[j]+VBC[j]))>1E-6) //sum not close to zero
                        thetavabc3[j]=pi+(atan((VAB[j]-VBC[j])/(-sqrt(3.0)*(VAB[j]+VBC[j])))); //the
angle lies in the second quadrant
                        else    //(if sum is close to zero, the angle is going to be either 90 or 270)
                                {
                                        int y=CDialog1Dlg::sign(VAB[j],VBC[j]);
                                //returns the sign of the difference between the two voltages (+ or -)
                                        thetavabc_view(j,e)=pi+y*pi/2;
                                }
                else
                {
                if (VAB[j]-VBC[j]<0)  //checks if the difference of the voltages is less than zero
                                        if (abs(-sqrt(3.0)*(VAB[j]-VBC[j]))>1e-6)
                                        //sum of the voltages greater than zero
                                                thetavabc3[j]=2*pi+(atan((VAB[j]-VBC[j])/(-
sqrt(3.0)*(VAB[j]+VBC[j])))); //the angle lies in the third quadrant
                                        else   //if sum is close to zero
                                        {
                                                int y=CDialog1Dlg::sign(VAB[j],VBC[j]); //returns
                        the sign of the difference between the two voltages (+ or -)
                                                thetavabc3[j]=2*pi+y*pi/2;
                                        }
                                        else
                                                if (abs(-sqrt(3.0)*(VAB[j]+VBC[j]))>1e-6)   //the
                                                remaining case: the first quadrant
                                                        thetavabc3[j]=(atan((VAB[j]-VBC[j])/(-
sqrt(3.0)*(VAB[j]+VBC[j])))); //the angle lies in the first quadrant
                                                else   //if sum is close to zero
                                                {
                                                int y=CDialog1Dlg::sign(VAB[j],VBC[j]);
                                //returns the sign of the difference between the two voltages (+ or -)
                                                        thetavabc3[j]=y*pi/2;
                                                }
                }
        }                                        //End of calculation of the angle between two phases
```

```
//Calculate the instantaneous phase-neutral rms voltage
        vector<double> vtrms1(rows), vtrms2(rows), vtrms3(rows);

        for (j=0; j<rows; j++)
        {
                vtrms1[j]=(-(VBC[j]+VCA[j])/(cos(thetavabc1[j]))/(sqrt(2.0)*VBase*sqrt(3.0)));
                vtrms2[j]=(-(VCA[j]+VAB[j])/(cos(thetavabc2[j]))/(sqrt(2.0)*VBase*sqrt(3.0)));
                vtrms3[j]=(-(VAB[j]+VBC[j])/(cos(thetavabc3[j]))/(sqrt(2.0)*VBase*sqrt(3.0)));
        }

        vector<double> Va(rows), Vb(rows), Vc(rows); //phase voltages

        for (j=0; j<rows; j++)
        {
                Va[j]=vtrms1[j]*sqrt(2.0)*VBase*cos(thetavabc1[j]-pi/6);
                Vb[j]=vtrms2[j]*sqrt(2.0)*VBase*cos(thetavabc2[j]-pi/6);
                Vc[j]=vtrms3[j]*sqrt(2.0)*VBase*cos(thetavabc3[j]-pi/6);
        }
//End of conversion of voltage from line-line to phase-neutral voltage

//Similar calculations are performed for getting the angle currents.
//The calculations are performed only for phase A.

        for (j=0; j<rows; j++)
        {
                        if (IB[j]+IC[j]>0)  //checks if the sum of the currents is greater than zero
                                if (abs(-sqrt(3.0)*(IB[j]+IC[j]))>1E-6) //sum not close to zero
                                        thetaia[j]=pi+(atan((IB[j]-IC[j])/(-sqrt(3.0)*(IB[j]+IC[j]))));
//the angle lies in the second quadrant
                        else    //(if sum is close to zero, the angle is going to be either 90 or 270)
                                        {
                                                int y=CDialog1Dlg::sign(IB[j],IC[j]);
                        //returns the sign of the difference between the two currents (+ or -)
                                                thetaia[j]=pi+y*pi/2;
                                        }
                        else
                        {
                        if (IB[j]-IC[j]<0)  //checks if the difference of the currents is less than zero
                        if (abs(-sqrt(3.0)*(IB[j]-IC[j]))>1e-6) //sum of the currents greater than zero
                                                thetaia[j]=2*pi+(atan((IB[j]-IC[j])/(-
sqrt(3.0)*(IB[j]+IC[j])))); //the angle lies in the third quadrant
                                        else    //if sum is close to zero
                                        {
                                                int y=CDialog1Dlg::sign(IB[j],IC[j]);
                        //returns the sign of the difference between the two currents (+ or -)
                                                thetaia[j]=2*pi+y*pi/2;
                                        }
                                        else
                        if (abs(-sqrt(3.0)*(IB[j]+IC[j]))>1e-6)
                        //the remaining case: the first quadrant
        thetaia[j]=(atan((IB[j]-IC[j])/(-sqrt(3.0)*(IB[j]+IC[j]))));
        //the angle lies in the first quadrant
```

```
                                                else   //if sum is close to zero
                                                {
                                                int y=CDialog1Dlg::sign(IB[j],IC[j]);
                        //returns the sign of the difference between the two currents (+ or -)
                                                        thetaia[j]=y*pi/2;
                                                }
                        }
        }                                                //End of calculation of the angle for phase A


//Calculate the rms current for phase A for each time step

        vector<double> Iarms(rows);

        for (j=0; j<rows; j++)
                Iarms[j]=-((IB[j]+IC[j])/(cos(thetaia[j]))/(sqrt(2.0)*IBase));



//Calculate the instantaneous machine generated emf by the formula
//ef=vt+(r+jxq)*Ia
//It was agreed upon between APS and ASU that for the best results (delta) the internal
//emf be calculated using Xq instead of Xd.
//To avoid using complex numbers, calculate real and complex parts separately

        vector<double> Efreal(rows), Efimag(rows), delta(rows);

        for (j=0; j<rows; j++)
        {
                Efreal[j]=vtrms1[j] + Iarms[j]*m_xq*cos(pi/2-thetapq[j]) + Iarms[j]*r*cos(-
                                                                thetapq[j]);
                Efimag[j]=Iarms[j]*m_xq*sin(pi/2-thetapq[j])+Iarms[j]*r*sin(-thetapq[j]);
                delta[j]=atan2(Efimag[j], Efreal[j]);
        }



//The instantaneous value of delta may contain large spikes which need to be smoothened out.
//The simple filter below disregards the new value and uses the previous value in
//the time series if the two adjacent values differ by 5 degrees. The figure 5 degrees is
//arbitrary and can be varied to obtain better results.

        for (j=1; j<rows; j++)
        {
                if (abs(delta[j]-delta[j-1])>= (5*pi/180))
                        delta[j]=delta[j-1];
        }
```

```
//Second filter for delta in addition to the one for the spikes.
//This is a moving average filter

        //First calculate the zero frequency component of the unfiltered delta
        double sum=0.0;
        for (j=0; j<rows; j++)
                sum+=delta[j];

        double deltaunfiltered_zerofrcomp=sum/rows;

        int run=20; //no. of terms in the moving average filter
        for (j=run; j<rows; j++)
        {
                sum=0.0;
                for (int e=(j-run); e<j; e++)
                        sum+=delta[e];

                delta[j-run]=sum/run;
        }

//Now calculate the zero frequency component of the filtered delta
        sum=0.0;
        for (j=0; j<(rows-run); j++)
                sum+=delta[j];

        double deltafiltered_zerofrcomp=sum/(rows-run);

//correct for the filter factor:
        for (j=0; j<(rows-run); j++)
                delta[j] *= deltaunfiltered_zerofrcomp/deltafiltered_zerofrcomp;

//Now rows becomes rows-run, since we used a MAF for delta
        rows-=run;

//end of calculating phase quantities and delta *****************************************


//transform abc voltages and currents into 0dq quantities *******************************

vector<double> theta(rows), I0(rows), Id(rows), Iq(rows), V0(rows), Vd(rows), Vq(rows);
        //the angle theta of Park's and the resulting 0dq vectors
vector<double> P21(rows), P22(rows), P23(rows),P31(rows), P32(rows), P33(rows) ;
                //the 2nd and 3rd rows of Park's matrix at each time step

        double P11, P12, P13;
        //the elements of the first row of the Park's transformation matrix (constant)

        P11=P12=P13=1/sqrt(3.0);
        for (j=0; j<rows; j++)
        {
                theta[j]=2*pi*m_frequency*t[j] + delta[j] + pi/2 + thetavabc1[0] - pi/6;
                                //the angle theta in the Park's transformation matrix
```

```
                    P21[j] = sqrt(2.0/3.0)*cos(theta[j]);
                    P22[j] = sqrt(2.0/3.0)*cos(theta[j]-2*pi/3);
                    P23[j] = sqrt(2.0/3.0)*cos(theta[j]+2*pi/3);
                    P31[j] = sqrt(2.0/3.0)*sin(theta[j]);
                    P32[j] = sqrt(2.0/3.0)*sin(theta[j]-2*pi/3);
                    P33[j] = sqrt(2.0/3.0)*sin(theta[j]+2*pi/3);

                    V0[j] = P11*Va[j] + P12*Vb[j] + P13*Vc[j]; //zero voltage component
                    Vd[j] = P21[j]*Va[j] + P22[j]*Vb[j] + P23[j]*Vc[j];
                    Vq[j] = P31[j]*Va[j] + P32[j]*Vb[j] + P33[j]*Vc[j];

                    I0[j] = P11*IA[j] + P12*IB[j] + P13*IC[j];
                    Id[j] = P21[j]*IA[j] + P22[j]*IB[j] + P23[j]*IC[j];
                    Iq[j] = P31[j]*IA[j] + P32[j]*IB[j] + P33[j]*IC[j];
            }

//End of Park's transformation **************************************************




//Begin filtering of rotor and stator quantities ******************************************

//Reads user's decision whether he wants to apply a full filter or not.
            int radioState_FullFilter;          //It will be assigned to 0 or 1 depending on state of button
            CButton* pRadio_FullFilter = (CButton*)GetDlgItem(IDC_FullFilter);
            radioState_FullFilter = pRadio_FullFilter->GetCheck();

//No matter what the decision is, we need to perform the following spike filter for all 0dq currents and
//voltages.  This filter compares successive sets of two measurements. If they differ by more than 10%,
//then measurement (k+1) is replaced by measurement k (all of the currents and voltages at that
//point. So basically the previous measurement is duplicated

            for (j=1; j<rows; j++)
            {
                    if (abs((V0[j]-V0[j-1])/V0[j-1])>(0.1) || abs((Vd[j]-Vd[j-1])/Vd[j-1])>(0.1) || abs((Vq[j]-
Vq[j-1])/Vq[j-1])>(0.1))
                            {
                                    V0[j]=V0[j-1];
                                    Vd[j]=Vd[j-1];
                                    Vq[j]=Vq[j-1];
                                    I0[j]=I0[j-1];
                                    Id[j]=Id[j-1];
                                    Iq[j]=Iq[j-1];
                            }

                    if (abs((I0[j]-I0[j-1])/I0[j-1])>(0.1) || abs((Id[j]-Id[j-1])/Id[j-1])>(0.1) || abs((Iq[j]-Iq[j-
1])/Iq[j-1])>(0.1))
                            {
                                    V0[j]=V0[j-1];
                                    Vd[j]=Vd[j-1];
                                    Vq[j]=Vq[j-1];
                                    I0[j]=I0[j-1];
```

```
                                    Id[j]=Id[j-1];
                                    Iq[j]=Iq[j-1];
                            }
                    }

//If he chooses not to use a full filter, then just use a 20pt moving average filter for
//the field quantities only.

//Create filtered matrices to be used by either the if or the else statement

            vector<double> V0filtered(rows), Vdfiltered(rows), Vqfiltered(rows), I0filtered(rows),
                            Idfiltered(rows), Iqfiltered(rows);
            vector<double> VFfiltered(rows), IFfiltered(rows);

            if (radioState_FullFilter==1)  //If the user selects the option to use a full filtering algorithm:
            {//do Butterworth filters
                                            }
            else
            {
//keep the 0dq signals as they are but put them in the "filtered" matrices for program continuity
                    for (j=0; j<rows; j++)
                    {
                            V0filtered[j]=V0[j];
                            Vdfiltered[j]=Vd[j];
                            Vqfiltered[j]=Vq[j];
                            I0filtered[j]=I0[j];
                            Idfiltered[j]=Id[j];
                            Iqfiltered[j]=Iq[j];
                    }
                    rows+=run;


                    //First calculate the zero frequency component of the unfiltered field signals

                    double sum1=0.0, sum2=0.0;
                    for (j=0; j<rows; j++)
                    {
                            sum1+=VF[j];
                            sum2+=IF[j];
                    }

                    double VFunfiltered_zerofrcomp=sum1/rows;
                    double IFunfiltered_zerofrcomp=sum2/rows;

                    int run=20; //no. of terms in the moving average filter
                    for (j=run; j<rows; j++)
                    {
                            sum1=sum2=0.0;
                            for (int e=(j-run); e<j; e++)
                            {
                                    sum1+=VF[e];
                                    sum2+=IF[e];
```

```
                            }
                            VFfiltered[j-run]=sum1/run;
                            IFfiltered[j-run]=sum2/run;
                    }


                    //Now calculate the zero frequency component of the filtered field quantities

                    sum1=0.0, sum2=0.0;

                    for (j=0; j<(rows-run); j++)
                    {
                            sum1+=VFfiltered[j];
                            sum2+=IFfiltered[j];
                    }


                    double VFfiltered_zerofrcomp=sum1/(rows-run);
                    double IFfiltered_zerofrcomp=sum2/(rows-run);


                    // correct for the filter factor:
                    for (j=0; j<(rows-run); j++)
                    {
                            VFfiltered[j] *= VFunfiltered_zerofrcomp/VFfiltered_zerofrcomp;
                            IFfiltered[j] *= IFunfiltered_zerofrcomp/IFfiltered_zerofrcomp;
                    }


            rows-=run;  // We make rows=rows-run again to keep the same variable for the rest of
                         // the program and to make sure that we delete the last 'run' elements in the
                         // other matrices
            }

//End of filtering of rotor and stator quantities *****************************************



//Calculate pu quantities of field and 0dq signals

        vector<double> V0pu(rows), Vdpu(rows), Vqpu(rows), I0pu(rows), Idpu(rows),
                        Iqpu(rows), VFpu(rows), IFpu(rows);

//convert field quantities to pu
        for (j=0; j<rows; j++)      // if no filtering was selected, rows is now rows-run, else it is
                                     // the same as before
        {
                VFpu[j]=VFfiltered[j]/VFBase;
                IFpu[j]=IFfiltered[j]/IFBase;
        }
```

```
//convert stator 0dq quantities to pu
        for (j=0; j<rows; j++)
        {
                V0pu[j] = V0filtered[j]/VBase;
                Vdpu[j] = Vdfiltered[j]/VBase;
                Vqpu[j] = Vqfiltered[j]/VBase;
                I0pu[j] = I0filtered[j]/IBase;
                Idpu[j] = Idfiltered[j]/IBase;
                Iqpu[j] = Iqfiltered[j]/IBase;
        }

//End of pu conversion ***********************************************************




//Calculation of the current derivatives ***************************************************
        vector<double> I0prime(rows-1), Idprime(rows-1), Iqprime(rows-1), IFprime(rows-1); //declare
current derivative vectors

        double deltat=t[1]-t[0];

        for (j=0; j<(rows-1); j++)
        {
                I0prime[j]=(I0pu[j+1]-I0pu[j])/deltat;
                Idprime[j]=(Idpu[j+1]-Idpu[j])/deltat;
                Iqprime[j]=(Iqpu[j+1]-Iqpu[j])/deltat;
                IFprime[j]=(IFpu[j+1]-IFpu[j])/deltat;
        }

//End of calculation of current derivatives ***********************************************




//Observer implementation ********************************************************
        // Declare vectors for damper currents and their derivatives
        vector<double> iD(rows), iQ(rows), iDprime(rows), iQprime(rows);

        //Find initial values of iD and iQ
        iD[0] = -(kMD/LQ)*deltat*Idprime[0]-(MR/LD)*deltat*IFprime[0];
        iQ[0] = -(kMQ/LQ)*deltat*Iqprime[0];

        //Now calculate iD and iQ
        for (j=0; j<rows-2; j++)
        {
                iD[j+1] = (1-(rD/LD)*deltat)*iD[j]-(kMD/LD)*deltat*Idprime[j]-
(MR/LD)*deltat*IFprime[j];
                iQ[j+1] = (1-(rQ/LQ)*deltat)*iQ[j]-(kMQ/LQ)*deltat*Iqprime[j];
        }

        //Find derivatives for iD and iQ:
        for (j=0; j<rows-3; j++)
        {
```

```
                        iDprime[j] = (iD[j+1]-iD[j])/deltat;
                        iQprime[j] = (iQ[j+1]-iQ[j])/deltat;
              }

//End of Observer Implementation *****************************************************



//Begin Estimator *********************************************************************
              rows-=3;                    //rows is now rows-3

              extern double X[16][2];        //X is external to enable access from different functions
              for (int e=0; e<16; e++)
                        for (int j=0; j<2; j++)
                                X[e][j]=0.0;        //initialize X
              w=1.0; //in per unit

//These are the R and L matrices resulting from Park's Transformation
              double R[6][6], L[6][6];

              for (j=0; j<6; j++)
                        for (int e=0; e<6; e++)
                        {
                                R[j][e] = 0;   L[j][e] = 0;
                        }

              R[0][0] = r+3*rn;
              R[1][1] = r;
              R[1][2] = w*Lq;
              R[1][5] = w*kMQ;
              R[2][1] = -w*Ld;
              R[2][2] = r;
              R[2][3] = -w*kMF;
              R[2][4] = -w*kMD;
              R[3][3] = rF;
              R[4][4] = rD;
              R[5][5] = rQ;

              L[0][0] = L0+3*Ln;
              L[1][1] = Ld;
              L[1][3] = kMF;
              L[1][4] = kMD;
              L[2][2] = Lq;
              L[2][5] = kMQ;
              L[3][1] = kMF;
              L[3][3] = LF;
              L[3][4] = MR;
              L[4][1] = kMD;
              L[4][3] = MR;
              L[4][4] = LD;
              L[5][2] = kMQ;
              L[5][5] = LQ;
```

//finished forming R and L matrices

//We want to formulate our data in the form H*x = Z where H is the matrix of the coefficients
//of the unknowns, x is the vector containing the unknowns and Z is the vector containing the
//measurements.

// Select elements to be estimated in the input dialog:
// At the same time, if a parameter is set to zero (selected), the proper state/states
// is/are assigned in matrix H, to save computation time (less 'for' loops).

```
        int rows1=6*rows; //number of rows in H and Z
        vector<double> H1(rows1), H2(rows1), H3(rows1), H4(rows1), H5(rows1), H6(rows1),
                        H7(rows1), H8(rows1);
        vector<double> H9(rows1), H10(rows1), H11(rows1), H12(rows1), H13(rows1),
                        H14(rows1), H15(rows1), Z(rows1);


        //Initialize to zero
        for (j=0; j<rows1; j++)
        {
                H1[j]=0; H2[j]=0; H3[j]=0; H4[j]=0; H5[j]=0; H6[j]=0; H7[j]=0; H8[j]=0;
                H9[j]=0; H10[j]=0; H11[j]=0; H12[j]=0; H13[j]=0; H14[j]=0; H15[j]=0;
                Z[j]=0;
        }



CDialog1Dlg::Onr3rn();
if (m_r3rn==TRUE)
{ R[0][0]=0;
        int j=0;
                for (int i=0; i<rows1; i+=6)
                        { H1[i] = I0pu[j]; j++;}
        X[0][1] =1;                  //parameter has been selected if 1
}


CDialog1Dlg::Onr();
if (m_r==TRUE)
{ {R[1][1]=0; R[2][2]=0;} //r occurs in two positions (not counting R[0][0]).
        int j=0;
                for (int i=1; i<rows1; i+=6)
                        { H2[i] = Idpu[j]; H2[i+1] = Iqpu[j]; j++;} //Therefore, it will result in two
                                                                    //assignments in H.
        X[1][1] =1;
}


CDialog1Dlg::OnLq();
if (m_Lq==TRUE)
{ {R[1][2]=0; L[2][2]=0;} //Lq occurs in two positions
        int j=0;
```

```
                for (int i=1; i<rows1; i+=6)
                        { H3[i] = w*Iqpu[j]; H3[i+1] = Iqprime[j];   j++;}
            X[2][1] =1;
}

CDialog1Dlg::OnLd();
if (m_Ld==TRUE)
{ {R[2][1]=0; L[1][1]=0; } //Ld occurs in two positions
        int j=0;
                for (int i=2; i<rows1; i+=6)
                        { H4[i] = -w*Idpu[j]; H4[i-1] = Idprime[j]; j++;}
            X[3][1] =1;
}

CDialog1Dlg::OnMF();
if (m_MF==TRUE)
{ {R[2][3]=0; L[1][3]=0; L[3][1]=0; } //MF occurs in three positions
        int j=0;
                for (int i=2; i<rows1; i+=6)
                        { H5[i] = -w*IFpu[j]; H5[i-1] = IFprime[j]; H5[i+1] = Idprime[j];        j++;}
            X[4][1] =1;
}

CDialog1Dlg::OnMD();
if (m_MD==TRUE)
{ {R[2][4]=0; L[1][4]=0; L[4][1]=0; } //MD occurs in three positions
        int j=0;
                for (int i=2; i<rows1; i+=6)
                        { H6[i] = -w*iD[j]; H6[i-1] = iDprime[j]; H6[i+2] = Idprime[j];        j++;}
            X[5][1] =1;
}

CDialog1Dlg::OnrF();
if (m_rF==TRUE)
{ R[3][3]=0;
        int j=0;
                for (int i=3; i<rows1; i+=6)
                        { H7[i] = IFpu[j];j++;}
            X[6][1] =1;
}


CDialog1Dlg::OnrD();
if (m_rD==TRUE)
{ R[4][4]=0;
        int j=0;
                for (int i=4; i<rows1; i+=6)
                        { H8[i] = iD[j];   j++;}
            X[7][1] =1;
}
```

```
CDialog1Dlg::OnL03Ln();
if (m_L03Ln==TRUE)
{ L[0][0]=0;
        int j=0;
                for (int i=0; i<rows1; i+=6)
                        { H9[i] = I0prime[j];        j++;}
        X[8][1] =1;
}

CDialog1Dlg::OnLF();
if (m_LF==TRUE)
{ L[3][3]=0;
        int j=0;
                for (int i=3; i<rows1; i+=6)
                        { H10[i] = IFprime[j];        j++;}
        X[9][1] =1;
}

CDialog1Dlg::OnMR();
if (m_MR==TRUE)
{ {L[3][4]=0; L[4][3]=0; } //MR occurs in two positions
        int j=0;
                for (int i=3; i<rows1; i+=6)
                        { H11[i] = iDprime[j]; H11[i+1] = IFprime[j];        j++;}
        X[10][1] =1;
}

CDialog1Dlg::OnLDdamper();
if (m_LDdamper==TRUE)
{ L[4][4]=0;
        int j=0;
                for (int i=4; i<rows1; i+=6)
                        { H12[i] = iDprime[j];        j++;}
        X[11][1] =1;
}
CDialog1Dlg::OnrQ();
if (m_rQ==TRUE)
{ L[5][5]=0;
        int j=0;
                for (int i=5; i<rows1; i+=6)
                        { H13[i] = iQ[j];  j++;}
        X[12][1] =1;
}

CDialog1Dlg::OnLQdamper();
if (m_LQdamper==TRUE)
{ L[5][5]=0;
        int j=0;
                for (int i=5; i<rows1; i+=6)
                        { H14[i] = iQprime[j];        j++;}
        X[13][1] =1;
}
```

```
CDialog1Dlg::OnMQ();
if (m_MQ==TRUE)
{ {R[1][5]=0; L[2][5]=0; L[5][2]=0; }    //MQ occurs in three positions
        int j=0;
                for (int i=5; i<rows1; i+=6)
                            { H15[i] = Iqprime[j]; H15[i-3]=iQprime[j]; H15[i-4]=w*iQ[j];          j++;}
        X[14][1] =1;
}
```

// Now, set up vector Z, which contains known parameters/measurements. Each set of 6 elements of Z is
//basically Equation (3.11) of dissertation, with all elements transfered to the RHS.
// If a parameter is desired to be estimated, it has been already set to zero previously.

```
        j=0;
        for (int i=0; i<rows1; i+=6)
        {
                Z[i]   = -V0pu[j] - R[0][0]*I0pu[j] - L[0][0]*I0prime[j];
                Z[i+1] = -Vdpu[j] - R[1][1]*Idpu[j] - R[1][2]*Iqpu[j]    - R[1][5]*iQ[j]    -
L[1][1]*Idprime[j] - L[1][3]*IFprime[j] - L[1][4]*iDprime[j];
                Z[i+2] = -Vqpu[j] - R[2][1]*Idpu[j] - R[2][2]*Iqpu[j]    - R[2][3]*IFpu[j]   -
R[2][4]*iD[j]    - L[2][2]*Iqprime[j] - L[2][5]*iQprime[j];
                Z[i+3] =  VFpu[j] - R[3][3]*IFpu[j] - L[3][1]*Idprime[j] - L[3][3]*IFprime[j] -
L[3][4]*iDprime[j];
                Z[i+4] = -R[4][4]*iD[j] - L[4][1]*Idprime[j] - L[4][3]*IFprime[j] - L[4][4]*iDprime[j];
                Z[i+5] = -R[5][5]*iQ[j] - L[5][2]*Iqprime[j] - L[5][5]*iQprime[j];
                j++;
        }          //Finished forming Z
double Ha=Z[1];
double Hb=Z[2];
double Hc=Z[3];
double Hd=Z[4];
double He=Z[5];
double Hf=Z[6];
```

// Declare Matrix Hdash and vector Zdash using the Linear Algebra package and copy into
// them H and Z respectively. This will enable the calculation of the pseudoinverse of H
// and the vector of the estimated parameters, x.

```
Matrix Hdash(rows1, 15); //The matrix is initialized to zero upon construction
Vector Zdash(rows1);              //The vector is initialized to zero upon construction

MatrixDA Hdasha(Hdash);  //Create a view of the matrix to copy elements of H to Hdash

        for (i=0; i<rows1; i++)
        {
                Hdasha(i+1,1)  = H1[i]; Hdasha(i+1,2)  = H2[i]; Hdasha(i+1,3)  = H3[i];
                Hdasha(i+1,4)  = H4[i]; Hdasha(i+1,5)  = H5[i]; Hdasha(i+1,6)  = H6[i];
                Hdasha(i+1,7)  = H7[i]; Hdasha(i+1,8)  = H8[i]; Hdasha(i+1,9)  = H9[i];
                Hdasha(i+1,10) = H10[i]; Hdasha(i+1,11) = H11[i]; Hdasha(i+1,12) = H12[i];
```

```
                    Hdasha(i+1,13) = H13[i]; Hdasha(i+1,14) = H14[i]; Hdasha(i+1,15) = H15[i];
                    //Copying of H completed
            }


for (i=0; i<rows1; i++)
            Zdash(i+1)=Z[i];    //Copying of Z complet
//Now do the pseudoinverse
SVD svd(Hdash);// Perform the SVD decomposition of matrix Hdash


// Compute the solution vector Xdash (=pinv(Hdash) *Zdash)
Vector Xdash = SVD_inv_mult(svd,Zdash);


//Now copy Xdash into X (normal c++ vector)
for (i=0; i<15; i++)
            X[i][0]=Xdash(i+1);    //Copying of X completed


//Calculation of rms error:
double residual=0.0;
double rms_error=0.0;

            vector<double> HXZ(rows1);  //=H*X-Z
            for (i=0; i<rows1; i++)
            {
HXZ[i]=X[0][0]*H1[i]+X[1][0]*H2[i]+X[2][0]*H3[i]+X[3][0]*H4[i]+X[4][0]*H5[i]+X[5][0]*H6[i]+X[6]
[0]*H7[i]+X[7][0]*H8[i]+X[8][0]*H9[i]+X[9][0]*H10[i]+X[10][0]*H11[i]+X[11][0]*H12[i]+X[12][0]*H
13[i]+X[13][0]*H14[i]+X[14][0]*H15[i]-Z[i];
            }

            for (i=0;i<rows; i++)
                    residual +=HXZ[i]*HXZ[i];

            residual = sqrt(residual);
            rms_error = residual/rows;

            X[15][0] = rms_error;

}

void CDialog1Dlg::OnrF() //If clicked, it assigns TRUE to this variable
{ CButton* prF = (CButton*)GetDlgItem(IDC_rF);
if (prF->GetCheck())
            m_rF = TRUE;
else m_rF = FALSE; }

void CDialog1Dlg::Onr()
{ CButton* pr = (CButton*)GetDlgItem(IDC_r);
if (pr->GetCheck())
            m_r = TRUE;
```

```
 else m_r = FALSE;}

void CDialog1Dlg::Onr3rn()
{ CButton* pr3rn = (CButton*)GetDlgItem(IDC_r3rn);
if (pr3rn->GetCheck())
        m_r3rn = TRUE;
else m_r3rn = FALSE;}

void CDialog1Dlg::OnLq()
{ CButton* pLq = (CButton*)GetDlgItem(IDC_Lq);
if (pLq->GetCheck())
        m_Lq = TRUE;
else m_Lq = FALSE;}

void CDialog1Dlg::OnLd()
{ CButton* pLd = (CButton*)GetDlgItem(IDC_Ld);
if (pLd->GetCheck())
        m_Ld = TRUE;
else m_Ld = FALSE;}

void CDialog1Dlg::OnMF()
{ CButton* pMF = (CButton*)GetDlgItem(IDC_MF);
if (pMF->GetCheck())
        m_MF = TRUE;
else m_MF = FALSE;}

void CDialog1Dlg::OnMD()
{ CButton* pMD = (CButton*)GetDlgItem(IDC_MD);
if (pMD->GetCheck())
        m_MD = TRUE;
else m_MD = FALSE;}

void CDialog1Dlg::OnrD()
{ CButton* prD = (CButton*)GetDlgItem(IDC_rD);
if (prD->GetCheck())
        m_rD = TRUE;
else m_rD = FALSE;}

void CDialog1Dlg::OnL03Ln()
{ CButton* pL03Ln = (CButton*)GetDlgItem(IDC_L03Ln);
if (pL03Ln->GetCheck())
        m_L03Ln = TRUE;
else m_L03Ln = FALSE;}

void CDialog1Dlg::OnLF()
{ CButton* pLF = (CButton*)GetDlgItem(IDC_LF);
if (pLF->GetCheck())
        m_LF = TRUE;
else m_LF = FALSE;}

void CDialog1Dlg::OnMR()
{ CButton* pMR = (CButton*)GetDlgItem(IDC_MR);
```

```
        if (pMR->GetCheck())
                m_MR = TRUE;
else m_MR = FALSE;}


void CDialog1Dlg::OnLDdamper()
{ CButton* pLDdamper = (CButton*)GetDlgItem(IDC_LDdamper);
if (pLDdamper->GetCheck())
                m_LDdamper = TRUE;
else m_LDdamper = FALSE;}


void CDialog1Dlg::OnrQ()
{ CButton* prQ = (CButton*)GetDlgItem(IDC_rQ);
if (prQ->GetCheck())
                m_rQ = TRUE;
else m_rQ = FALSE;           }


void CDialog1Dlg::OnLQdamper()
{ CButton* pLQdamper = (CButton*)GetDlgItem(IDC_LQdamper);
if (pLQdamper->GetCheck())
                m_LQdamper = TRUE;
else m_LQdamper = FALSE; }


void CDialog1Dlg::OnMQ()
{ CButton* pMQ = (CButton*)GetDlgItem(IDC_MQ);
if (pMQ->GetCheck())
                m_MQ = TRUE;
else m_MQ = FALSE; }



int CDialog1Dlg::next(int e)           //used to obtain the next phase in the sequence A-B-C-A
{
        int phase;
        if (e==3)
                    phase=1;
        else
                    phase=e+1;

        return phase;
}

int CDialog1Dlg::sign(double V1, double V2)  //returns the sign of the difference of two numbers
{
        if (V1-V2>0)
                    return 1.0;
        else
        {
                    if (V1-V2<0)
                    return -1.0;
                    else
                            return 0.0;
        }
}
```

```
void CDialog1Dlg::OnKillfocusS3Base() //If changed removes previous default value from the respective
edit box
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocusV3Base()
{        UpdateData(TRUE);  }


void CDialog1Dlg::OnKillfocusIfieldairgap()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocusfrequency()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocusrn()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocusLn()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocusxd()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocusxq()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocusxprimedv()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocusxdoubleprimedv()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocusxdoubleprimeqv()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocusx0()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocusxLm()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocusR1()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocustauprimedzero()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocustaudoubleprimed()
{        UpdateData(TRUE);  }

void CDialog1Dlg::OnKillfocustaudoubleprimeqzero()
{        UpdateData(TRUE);  }
```